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THESIS

THE DEVELOPMENT AND USE OF DISTRIBUTION SYSTEM MODELS FOR IMPROVING THE SECURITY OF DRINKING WATER SYSTEMS

Submitted by

John S. Frazey

Department of Civil Engineering

In partial fulfillment of the requirements

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Colorado State University

Fort Collins, Colorado

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ABSTRACT OF THESIS

THE DEVELOPMENT AND USE OF DISTRIBUTION SYSTEM MODELS FOR IMPROVING THE SECURITY OF DRINKING WATER SYSTEMS

Guidance was developed for water system distribution software application to security related uses. This guidance was broken into four uses: model development, pre-scenario analysis, post-scenario analysis, and detector placement analysis. This guidance allows a water utility to take a water modeling program, develop it, and then analyze how water systems will respond to different water security scenarios. This will help the utility determine areas of vulnerability. This guidance will also allow the utility to evaluate the siting of detectors. Additionally, it will also allow analysis of post-scenario responses to determine the travel of any contaminant that may have been introduced into the system. The detectability of *Cryptosporidium parvum* was then analyzed using normally water quality parameters, including turbidity, total organic carbon, pH, chlorine residual, and conductivity. The detection levels for this contaminant was then calculated, which was based on a statistically significant change in these parameters. This statistically significant change was the 3-sigma value. *Cryptosporidium parvum* was analyzed in the model using the modeling guidance with four different scenarios that were developed to determine the influence of feed methodology and location. The assumptions of the amount of *Cryptosporidium parvum* that could potentially be available were determined from the literature review. The results of the modeling showed that the *Cryptosporidium parvum* would be capable of producing widespread system contamination. This type of contamination would not likely produce a large number of fatalities, but there would be widespread illnesses caused throughout the system. It was found that contamination efficacy is dependent more on location of the backflow rather than the pumping method. The detection methods evaluated would detect the contaminant, but at concentrations much greater than the infective dose. This detection would allow a utility to identify the problem and begin to respond.

John S. Frazey

Department of Civil Engineering

Colorado State University

Fort, Collins, CO 80523

Summer 2004

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CHAPTER 1. INTRODUCTION

The attacks on the United States on September 11, 2001, showed that this country is vulnerable to terrorist attack. There is now a renewed focus on protecting the country from another attack, which has included evaluation of all vulnerabilities. One vulnerability is the drinking water systems. The water supplied through these systems is usually taken for granted to be safe and reliable; however, there has been a fundamental shift in how terrorists operate—they will now stop at nothing to attack our country through the exploitation of any vulnerability, including the water system.

If a terrorist were to attack a water system, hundreds of thousands could be impacted at once. These systems have not been a focus for security improvements because they have not been attacked in the past. These systems are vulnerable to attack, which is thoroughly explained in the literature review.

The overall goal of this research was to evaluate commonly used water distribution tools and provide guidance on their application for security applications. These tools include water distribution modeling software and simple water quality instruments. For instance, water distribution modeling software is in widespread use, but this software has not been applied to a great extent to security specific issues. There are many different methods in which they could be applied to security issues. Other tools that could be used for security issues include the monitoring equipment already in use (turbidimeters, pH monitors, chlorine analyzers, etc). There is research available on the

use of these instruments for detecting chemicals in the water system, but there is very limited research on using these instruments for detecting microbiological contaminants. Therefore, another goal of this research was to evaluate the ability of these instruments to detect microbiological contaminants. The goals and objectives are listed in Chapter 3.

As the water utility increases in size, so do the resources available. The smaller utilities have very limited resources and could conceivably be more vulnerable to an attack. This guidance is pertinent to large utilities also, especially the monitoring data. If microbiological contaminants can be detected by simple monitoring equipment, large utilities could leverage their resources even more by increasing the number of monitoring stations. Based on this, the guidance developed and evaluated in this paper is applicable to all utilities.

This paper would serve as a starting point for model application to security issues. Chapter 4 describes the water models that are available for use, with the guidance developed and explained in Chapter 6. Chapter 5 describes the microbiological detection, which is then applied to a model in Chapter 7. Through this research, the ability to increase security applications through normally used tools is explored.

CHAPTER 2. LITERATURE REVIEW

In 2001, there were 54,064 municipal water systems across the United States (Dreazen, 2001). The customers in each of these municipalities expect and demand clean, safe water. This may be becoming more difficult to provide with the increased threat of terrorism. Gay Porter DeNileon, a journalist who serves on the National Critical Infrastructure Protection Advisory Group, stated, "one sociopath who understands hydraulics and has access to a drum of toxic chemicals could inflict serious damage pretty quickly" (Dreazen, 2001). This threat is causing some water utilities to take additional precautions to prevent terrorists from attacking the water system, particularly through the reversal of flow into homes and businesses. Some of these corrective measures include monitoring system-wide pressure (now being done in St. Petersburg, Florida) and alarms triggered by smaller pressure drops (done in Portland, Oregon) (Dreazen, 2001).

2.1 General Terrorism

There has been a fundamental change in how terrorism is executed. In the 1970s and 1980s, terrorists had clear political objectives and their attacks were meant to produce just enough bloodshed to get attention for their cause, but not so much that their public support would be alienated. Terrorists now kill as many people as possible. The goal of terrorism is not only to destroy life, but also our system of government, which makes it not only increasingly dangerous, but also more difficult to stop (National

Commission on Terrorism, 2000). The new terrorist groups represent a growing trend of hatred toward the United States. They have thus far only used conventional weapons, but there is now interest in nuclear, biological, and chemical (NBC) weapons. Most experts agree that the terrorists are now pursuing these NBC weapons (National Commission on Terrorism, 2000). An attack, if done using NBC weapons and only partially successful, could profoundly affect the entire nation, especially if the goal is just to challenge Americans' sense of safety (National Commission on Terrorism, June 2000).

Past attacks using only conventional weapons have shown the susceptibility of the United States. In 1993 terrorists attacked the World Trade Center, killing six and wounding about 1,000 others. Several other attacks at the same time were thwarted, including bombings of several tunnels. Bombs also destroyed the military barracks in Saudi Arabia and two U.S. African Embassies, inflicting 6,059 casualties (National Commission on Terrorism, June 2000). Other potential attacks have been thwarted. In December 1999, arrests were made in Jordan and at the U.S.—Canadian border of foreign nationals who were allegedly planning to attack crowded millennium celebrations. This is a large threat itself because on an average day, over one million people enter the U.S. legally, and thousands more enter illegally (National Commission on Terrorism, June 2000). These attacks do not even include the attacks on September 11, 2001, when over 3,000 Americans lost their lives.

There are recent examples of terrorist attacks using NBC material. In Dalles, Oregon, the Rajneeshee religious cult contaminated a salad bar using vials of *Salmonella typhimurium*, a highly toxic bacterium carried by birds, which the cult had cultured. There were 751 documented illnesses following the attack, in a county that usually only

has five per year (McDade and Franz, 1998). In 1995, the apocalyptic group Aum Shinrikyo released sarin, a chemical agent, in the Tokyo subway. The efforts by this group demonstrated the difficulties that terrorists face when using these types of weapons. The group used many highly skilled technicians and spent tens of millions of dollars developing a chemical attack that killed fewer people than conventional explosives could have. The same group completely failed in a separate attempt to launch an anthrax attack in Tokyo (National Commission on Terrorism, 2000).

2.2 Water System Susceptibility

Deliberate chemical and biological contamination is not new (Hickman, 1999; Deininger, 2000; Clark and Deininger, 2001) and some of these attacks have been on the water systems. For instance, in biblical times, the Nile River was turned to "blood", which was the first plague of the Book of Exodus forcing all Egyptians to use wells as an alternate supply. Cyanide was used in ancient Rome to poison the water. Soldiers during the American Civil War shot and left farm animals in ponds, thus poisoning the water, so that advancing troops could not use the water. In 1941, J. Edgar Hoover recognized the threat of water system sabotage, stating "water supply facilities offer a particularly vulnerable point of attack to the foreign agent." In WWII, water supplies were intentionally contaminated in China with bacteria and in Bohemia with sewage. Anthrax and cholera were also used in Europe and Asia during WWII to contaminate water. Most recently, paints, oil, and gasoline were placed in wells during the conflict in Kosovo (Haested Press, 2003). All of these attacks resulted in water quality degradation to some extent.

There have been examples of water system susceptibility from NBC in this country. In 1986, the New York Times reported that low levels of plutonium were found in New York City drinking water. This was on the order of 20 femtocuries, where background is usually 1 femtocurie (New York Times, 1986). There have also been several cases of accidental contamination that have caused widespread illness. The pathogens involved have ranged from *E. coli* in Walkerton, Ontario, to cholera contamination in Peru (Craun et al, 1991), to *Cryptosporidium parvum* in Milwaukee (Fox and Lytle, 1996), and *Salmonella* in Gideon, MO (Clark et al, 1996). Recently, Canadian police and security officials warned that Al Qaeda might try to contaminate food or water with toxins. Secret intelligence reports by the Privy Council Office expressed concern that they could use lethal substances such as ricin and botulinum toxin (Bronskill, 2003).

This problem is only exacerbated by the lack of control for transfers of certain substances. For example, the National Commission on Terror found that biological transfer controls are largely inadequate and controls on related equipment are nonexistent (2000). Most pathogens in the US are tightly controlled, but a terrorist group could obtain them from domestic natural sources, steal them, or import them. Most places that store biological agents in the U.S. have controls to prevent accidents, but not necessarily theft. Where controls are present, they are not nearly as tight as for nuclear material. Some of these NBC materials could easily be obtained from a foreign state and there are nations attempting to make these materials—five out of the seven nations the U.S. identifies as state sponsors of terror have programs to develop weapons of mass destruction (National Commission on Terrorism, 2000).

An attacker could exploit several different vulnerabilities. The President's Commission on Critical Infrastructure concluded that drinking water utilities are vulnerable to physical, cyber, and biological terrorism. The characteristics that make them especially vulnerable to attack include the facts that they are spatially distributed, susceptible to intrusion, and contain many components (Clark and Deininger, 2001).

An attack could be as simple as a physical interruption of service. Because many water systems have custom-designed equipment, a physical attack could take months to repair, exposing several vulnerabilities. These vulnerabilities would include disabling of fire-fighting capability, service interruption, diminished public confidence, and economic impacts. Such an attack could have large economic impacts. It has been estimated that the loss of water flow to agriculture and industry for only one growing season could result in the loss of billions of dollars (Clark and Deininger, 2001).

Another vulnerability of the system is chemical and biological contaminations. Containment of these weapons has not been the focus of domestic planning and today they are readily available to many countries and rouge states. Based on this availability and the willingness for some groups to use these, a serious and credible threat now exists. The probability of use is greater than ever (Waeckerle, 2000). The potentially devastating consequences could cause widespread death, disease, and destruction of infrastructure, and possibly society itself (Nunn-Lugar-Domenici Amendment, 1996 and Jenkins, 1997).

Use of these weapons in water systems has historically not been the focus of domestic planning (Waeckerle, 2000). Because of this, even though there is information

about dispersal of these agents into the air, there is little known about dispersal of these agents into water (Waeckerle, 2000).

There are numerous potential points of for intentional contamination. First there is the water treatment plant. The clearwells located at the end of the treatment plant would be the most vulnerable location inside a plant. Second, pump stations and valves are another potential source. There is a large amount of flow passing through these points at any given time; therefore, any contaminant injected here could impact many downstream customers. Third, finished tanks and reservoirs within the system are also potential contamination points. These are generally in isolated locations and they normally have some type of access for maintenance. An attack on these would also have a large impact through the system. Another potential contamination source are hydrants. There have been no recorded instances of saboteurs using hydrants, but there have been cases of accidental backflow from tankers being filled directly from hydrants. Finally, distribution system connections also offer a source for contamination. Any pump capable of overcoming system pressure could inject contaminants into the system through backflow and thereby impact nearby customers or larger areas. The amount of contamination would depend on several factors, including the location and the amount of contaminant pumped into the system (Haested Press, 2003).

Backflow threats have been analyzed more thoroughly since the attacks on September 11, 2001. Backflow into a system can be accomplished with a vacuum cleaner or bicycle pump. The distribution system is the biggest threat, according to John Sullivan, chief engineer for Boston Water and Sewer Commission and past president of the Association of Metropolitan Water Agencies (Dreazen, 2001):

> “There's no question that the distribution system is the most vulnerable spot we have. Our reservoirs are really well protected. Our water-treatment plants can be surrounded by cops and guards. But if there's an intentional attempt to create a backflow, there's no way to totally prevent it."

It would take a large amount of contaminant to impact a reservoir based on the size and the removal at the treatment plant, but a backflow could impact thousands of homes and businesses (Dreazen, 2001). There is also little money obligated to this threat. EPA spending to combat bio-terrorism in 2001 was $2.5 million, up from $10,000 in 1998, none in 1999, and $100,000 in 2000. The amount that municipal and private water-system officials requested for 2002 was $155 million, while the same year the amount requested to improve water utilities was $5 billion (Dreazen, 2001).

2.3 Water System Background

Understanding the nature of the water distribution system is an important step towards determining the risks due to contamination and then mitigating these risks. Each area of the system presents special situations that may degrade water quality, thus making an attack more likely, less detectable, or increased in severity.

The water treatment plant is the primary barrier, but it is not effective against all attacks (Haested Press, 2003), and is obviously not effective for attacks after the plant. After the treatment plant, the only effective barrier is the disinfectant residual. Proper maintenance of this residual is an important protection and in order to maintain that protection, knowledge of the system is required. Water quality degradation can result from a number of factors, including the decay of disinfectant residual, the generation of a contaminant within the distribution system (e.g. disinfection byproducts), or the

occurrence of contamination originating from a point source (Clark, Grayman, and Males, 1988).

Some of the system problems that may lead to increased vulnerabilities are difficult to control, as seen by system age in most areas. Most of the water systems in this country were established between the turn of the century and the 1930s (Clark, Grayman, Males, 1993). Couple this with the fact that most of the capital expenditures of the system are for the distribution system, and the redesign or reconstruction of a system to meet water-quality goals is a serious issue, especially considering that the distribution system accounts for more than 80% of the total water utility investment (Clark, Grayman, Goodrich, Deininger, and Skov, 1994). A normal medium-sized utility may have thousands of kilometers of pipes constructed from various types of different material, ranging from new lined pipe to pipe over 50-years old (Clark, Grayman, Males, 1993).

It is a known fact that the longer water is in the system, the more likely it will degrade in quality. This includes not only chlorine decay, but also the increase of disinfectant byproducts increase (Clark et al, 1994). Water quality degradation in the system can be a consequence of two main reasons: decay or growth of non-conservative constituents that takes place during the transport process (Boulos, Altman, Jarrige, and Collevati, 1994), or accidental intrusion of contaminants (Kessler, Ostfeld, and Sinai, 1998). The first reason can be further broken into the following: loss of disinfectant, temperature changes, flow velocity changes, biofilm sloughing and stirred-up pipe sediments caused by rapid changes in flow or even flow reversals, regrowth of bacteria that survived treatment, or growth of bacteria in biofilm (AWWA, 1999c). The second can be attributed to pipe breaks and replacements, instructions of contaminants from

pressure drops, and cross-connections (AWWA, 1999c). These system degradations are important considerations because they will affect the degree that the water is impacted through any contamination.

As mentioned above, the water treatment plant is the main defense against contamination with the next defense being disinfectant residual in system, which provides some protection, but is not effective for all (Haested Press, 2003). The Surface Water Treatment Rule requires 0.2 mg/L of chlorine or 0.04 mg/L for chloramines in the finished water, which may control the growth of microbiologicals in water, but not all growth, especially biofilm growth (AWWA, 1999c). Information about chlorine residual is key to protecting the system because chlorine is a very important defense mechanism. Any area in the system that has lower chlorine residuals would be an area that may be more susceptible to an attack.

Previous studies have shown that chlorine residuals can change dramatically throughout the system (Clark et al, 1994). The distribution system can have negative impacts on chlorine residuals, with many items impacting it including pipe-wall demand, residence time, velocity, pipe radius, and bulk water demand. These conditions usually make it difficult to maintain chlorine residuals (Clark, Rossman, and Wymer, 1995). Past studies have shown that free and total chlorine residuals dropped rapidly as distance from the plant increased and they could not, in fact, be detected in distant parts of the system where HPC levels were highest (Lu, Biswas, and Clark, 1995).

The chlorine demand also depends on the type of pipes in the system. Unlined cast-iron pipes have higher chlorine consumption than polyvinyl chloride (PVC). Also, larger-diameter cast-iron pipe has lower consumption than smaller-diameter pipe (Clark,

Rossman, and Wymer, 1995). The water can have an impact also—water high in humic and organic material that is transported in the network can lead to pipes with a high disinfectant demand (Clark, Rossman, and Wymer, 1995). Biofilm on iron pipes were much more resistant to free chlorine than those grown on galvanized, PVC, or copper pipe surfaces. This is probably due to the fact that free chlorine is known to react more with ferrous iron to produce insoluble ferric hydroxide (Lu, Biswas, and Clark, 1995).

Another problem impacting water quality is water main breaks, which can be caused by many different actions in older systems including temperature variation, large swings in water pressure, traffic and industrial vibration, and accidents (Clark and Deininger, 2001). A water main break would be a potential area for contamination injection. Breaks are also important because they can have major detrimental impacts on the system, that is, introduction of impurities.

In a typical system, many heterotrophic bacteria survive and pass on to the low nutrient (oligotrophic) conditions of treated drinking water. Once they arrive in the system, they have certain advantages that suit their survivability. These advantages include the ability to associate, temporarily or by colonization. The nutrients in the system are at low levels, thus bacteria on the pipe walls have the advantage in that they have a continuous nutrient supply. These bacteria that have adapted to the low nutrient conditions are more tolerant to disinfectants. The typical biofilm density is about $1x10^5$ to $1x10^8$ colony forming units/cm^2. The nutrients for many biofilm organisms are biodegradable organic carbon (BDOC) and assimilable organic carbon (AOC) (AWWA, 1999c). Some types of treatment (preoxidation) before filtration can increase the AOC, which can stimulate bacterial growth in the system. Heterotrophic growth or re-growth is

most likely to occur when the disinfectant drops below 0.2 mg/L, in water temperatures greater than 10° C, and if the AOC is greater than 50 μg/L (AWWA, 1999c). Awareness of this and other potential problems will assist in maintaining the system properly. The type of pipe has an impact of the biofilm also. Biofilm on iron pipes is much more resistant to free chlorine than those grown on galvanized, PVC, or copper pipe surfaces. This is probably because free chlorine reacts more with ferrous iron to produce insoluble ferric hydroxide (Lu, Biswas, and Clark, 1995). In systems where biofilms and tubercles are attacked to the pipe walls, a significant loss of disinfectant residual can occur, which can adversely impact water quality (Clark, Grayman, Males, 1993). Biofilms are an important consideration because they can degrade the chlorine residual and they can also affect the wall reaction coefficients, which are an important consideration in water modeling.

Another major part of the system that can impact water quality is the storage. Direct pumping of water could maximize water quality, but is rarely done today (AWWA, 1989). The design of distribution systems is frequently done to ensure hydraulic reliability, adequate water quantity, and meet fireflow demands. To meet these demands, large amounts of water must be placed in storage throughout the system (Clark, Rossman, and Wymer, 1995). Utilities are required to provide reliable service and adequate reservoir capacity for fireflow, as required by the Insurance Service Office rating system. Because of this, many states have design standards for minimum storage requirements, but not maximum. Thus there can be long storage times for water in tanks, which forces a serious conflict between reliability issues and minimizing detention time (Clark, Grayman, Males, 1993).

These tanks are used to meet the diurnal variation of water in system, so they are typically filled for ½ of the day, with the rest of the day emptying. During the day, the water supplies are normally fed to the system from the top 10 to 15 feet of water from the tank, with the remaining water in the tank (70 to 75%) held in reserve as dedicated fire storage. Based on this, chlorine residuals can virtually disappear (Clark et al, 1994). This diminishes one of the major defenses against system contamination. Additionally, the storage within the system could serve as a place for contamination and could act as a reservoir storing the agent.

Another key parameter for water quality is backflow. The Foundation for Cross-Connection Control and Hydraulic Research (FCCCHR) at the University of Southern California defines backflow as a flow of nonpotable water, or any other substance, back into the potable water distribution system (USC FCCCHR, 1993). This can either be through backsiphonage or backpressure (USC FCCCHR, 1993; BMI, 1996). Backsiphonage is a backflow caused by either negative or sub-atmospheric pressure in part of the system or the supply piping (USC FCCCHR, 1993). These can be caused by water main breaks and any other activity that causes water to be withdrawn from the system at a high rate, such as firefighting. Backpressure is when a nonpotable system is connected to a potable supply through a higher pressure method, such as a pump or elevation difference (USC FCCCHR, 1993). Unlike backsiphonage, backpressure does not require a drop in system pressure and will occur whenever pressure at the cross-connection exceeds that of the system. Even under normal circumstances, there is a high risk for system contamination when these are not properly protected (USC FCCCHR, 1993). Backpressure can occur with pressurized systems that use pumps for chemical

feeds, boosters, fire protection or cooling system (USC FCCCHR, 1993; FDEP, 2001). Chances of these increase when the system pressure drops to below normal pressures, based on changes in valve setting, pipeline breaks, air valve slams, loose-fitting service meter connections, surge or feed tank draining, or a sudden change in demand (Kirmeyer et al, 2001).

Detection of backflows can be difficult, but is possible because of pressure drops in the targeted area. After a pressure drop, the pressure may then climb as flow is reversed. These pressure drops can be detected, but will be more difficult as the pipes get smaller (Dreazen, 2001). There are indicators that a backflow incident has occurred. These indicators include customer complaints of water quality (odor, color, and taste) as well as drops in pressure or disinfectant residual, water meters running in reverse, or coliform detections (USEPA, 2002a). One study of water systems showed that during pump tests, routine operations, or power outages, pressures as low as –10.1 psi were recorded for durations from 16 to 51 seconds. During this time, the chances of backflow increased (LeChevallier, Gullick, and Karim, 2001). The study also showed that a surge generated by simulated power failure to pump estimated that 69 gallons of external water could intrude within 60 seconds (LeChevallier, Gullick, and Karim, 2001).

The literature includes several examples of waterborne diseases and illnesses that were caused by backflow. These are discussed more in-depth later.

2.4 Waterborne Diseases Caused by Backflows

Data on past backflows is available through several organizations: Centers for Disease Control and Prevention, Cross-Connection Control Committee of the Pacific Northwest Section of the American Water Works Association (AWWA PNWS),

University of Southern California's Foundation for Cross-Connection Control and Hydraulic Research (USC FCCCHR), and the American Backflow Prevention Association (ABPA) (USEPA, 2002a). There have been several reported backflow incidents, but these numbers can be misleading because there are no national reporting requirements for these incidents. The incidents may be underreported because some contamination, especially bacterial contamination, is usually transient and highly localized (ABPA, 1999). The number of incidences reported is thought to be very small compared to what has actually occurred. Part of the reason for this is that simple backflows can be created without knowledge, such as a garden hose submerged in pesticides (USEPA, 2002a). The actual extent of the contamination depends on several factors, including location, concentration, and magnitude and duration of the pressure difference. The occurrence is directly related to system pressure, but any pressure differential can lead to backflow (USEPA, 2002a).

The EPA estimates that 459 backflow incidents occurred in the US from 1970 to 2001 impacting an estimated 12,093 people (USEPA, 2002a). AWWA estimates that contamination of water in the distribution system from corrosion products, cross-connections and backsiphonage, inadequately protected storage facilities, and repairs to water mains and plumbing were responsible for 22% of waterborne outbreaks reported from 1991 to 1996. From 1920 to 1990, contamination of distribution systems caused 11 to 18% of all outbreaks (AWWA, 1999b). Another AWWA study estimates that up 78% of waterborne illnesses may be based on cross-connections and backflow (AWWA, 1999c). Yet another survey of 70 systems conducted by the ABPA reported that 11,186

pressure reduction incidents occurred in one year—34.8% were from routine flushing, 19.2% were from main breaks, and 16.2% were due to service line breaks (ABPA, 2000).

The health impacts of backflows are usually gastrointestinal disorders, which can also make the reporting more difficult. Past estimates from the CDC have focused on the causes of these diseases; however, the CDC has somewhat strict criteria, so the actual results may be much higher (USEPA, 2002a). The data from the CDC estimated that from 1981 to 1998, there were 57 waterborne diseases related to cross-connections, resulting in 9,734 illnesses. This was further broken down into specific causes: microbiological contaminants caused 20 outbreaks (6,333 cases of illness); chemicals caused 15 outbreaks (679 cases of illness); and there were 22 outbreaks (2,722 illnesses) where the contaminant was not reported (USEPA, 2002a). The EPA estimated that from 1971-1998, 30.3% of the waterborne disease outbreaks in community water systems were caused by contamination of water in the distribution systems (USEPA, 2002a). Of these, up to 50.6% were caused by cross-connection and backflow (Craun and Calderon, 2001). These backflows caused up to 95% of all waterborne disease outbreaks that were are associated with distribution contamination in community water systems (AWWA, 1999c).

The likelihood and severity of illness and number affected depends on several factors, including amount of contamination, dilution factor, number of users, and health of each exposed. Contamination can occur upstream and downstream as contaminants spread. The fate and transport of each is difficult to predict and depends on system hydraulics and the contaminant (USEPA, 2002a).

Chemical contaminants are rarely reported because they usually occur with the greatest frequency in private residences, the illnesses present non-specific symptoms, and the detections are not well established (CDC, 1996). The most common chemical contaminants include copper, chromium, ethylene glycol, detergents, chlordane, malathion, propylene glycol, freon, and nitrite (USEPA, 2002a). Pesticides have been reported in 45 incidents, which have included chlordane, malathion, heptachlor, and diazinon (contaminants in 11, 5, 3, and 2 incidents, respectively). There have been 73 reported incidents with metals, including 55 with copper and 18 with hexavalent chromium; 66 reported incidents with synthetic and volatile organic compounds; 16 reported incidents from ethylene glycol; 5 reported incidents from propylene glycol, and five incidents from nitrates and nitrites (USEPA, 2002a).

There are some examples of backflows in the literature, all of which have been accidental. One example of backpressure was seen with a Connecticut gas company when workers purged propane tanks and did not know the propane was at a greater pressure than the water line, thus causing a backflow which started fires and the evacuation of two homes (USEPA, 1989). Another backpressure event occurred in 1991 in Tucumcari, NM, in a facility making ethanol. An unprotected auxiliary water line feeding emergency fire cannons was tapped illegally into a hose connected to the plant's flushing system. After flushing and normal operations started, numerous chemicals were injected into the system, including toluene, phenol, benzene, ethanol, nonanoic acid, decanoic acid, octanol, octanoic acid, heptanoic acid, butanoic acid, silicon, diconic acid and four trihalomethanes. The levels were high enough that the mayor and several others became very ill for 48 hours, but there were no deaths (AWWA PNWS, 1995).

In 1997, fire-fighting foam was put into the water system in Charlotte, NC. Thousands were told not to shower or drink the tap water for several days. In 1988 in Bridgeport, Connecticut, workers at a United Technologies Corporation Sikorsky helicopter plant added corrosion protection chemicals to the facility's fire prevention system to guard against corrosion, some of which backed into the water supply and into homes. Residents were told not to drink or use the water for days (Dreazen, 2001).

Other examples of backflow have been based on fires, which can have detrimental impacts on the system through pressure reductions (AWWA, 1999c). In 1974 in Washington, a fire-fighting effort caused backsiphonage of a chemical and other pollutants into potable water system (AWWA PNWS, 1995). Hydrant flushing, pump repair, valve replacements, etc., can have the same results (USEPA, 2002a).

System maintenance, if not done properly, can also have detrimental impacts on the system. In South Carolina in 1978, 15 people became ill when chlordane was backsiphoned from an exterminator truck during a meter repair (USC FCCCHR, 1993). In Bancroft, MI, in May 1982, crews shut down a main to replace a valve. The resulting pressure loss caused a backflow of malathion from a hose end applicator. The action resulted in loss of water to the town for two days (USC FCCCHR, 1993). In 1987 in Gridley, KS, the herbicide Lexon DF was backsiphoned from a tanker truck when main broke during excavation. This incident contaminated ten residences and one business (USC FCCCHR, 1993).

Biological contaminants can also impact the system. The risks for biological contamination from backflow vary largely based on the disease vector, the concentration, the agent infectivity, the disinfectant level, and the individual's health (Rusin, Rose,

Haas, and Gerba, 1997). High numbers of the pathogen may be required for healthy hosts using the oral route, up to 10^6 to 10^{10} cells are needed for infection (Rusin et al, 1997). There are some examples of backflow biological contamination in the literature. *Giardia lamblia* and some strains of *E. coli* have contaminated potable water through cross-connection with sewer lines, untreated water sources, reclaimed water supplies, medical and mortuary equipment, utility sinks, and pools (USC FCCCHR, 1993). Other primary sources of contamination include drain lines, laboratories, and illegal connections of private wells to public water supplies (USC FCCCHR, 1993). A majority of these were listed as sewage or non-specific (32 out of 58). One occurred in the summer of 1990 when 1,100 people from a Tennessee country club suffered from intestinal disorders when they consumed contaminated water from the club after an auxiliary well had become contaminated with sewage due to a cross-connection (AWWA PNWS, 1995). Another example occurred in February 1990, in Seattle after a cross-connection occurred between an auxiliary irrigation system supporting a country club and the city's water system. This resulted in total and fecal coliform contamination in the water (AWWA PNWS, 1995).

Part of the problem with reporting backflow contamination events is that the reports are not necessarily specific on the symptoms. There are, however, some specific disease details that were collected by the EPA and these are discussed below.

- *Shigella* has been reported in five incidents. It is a cause of gastroenteritis, as well as vomiting, diarrhea, fever, and convulsions (USEPA, 2002b). All species are highly infectious and spread through fecal contamination (USFDA, 2001a). In 1977, there

were four cases in an apartment house in Chicago, Illinois (USC FCCCHR, 1993), but it was not known if it was spread through the distribution system.

- *E. coli* is a common contaminant found in sewage and usually a benign intestinal bacterium present in all humans. Some strains are pathogenic, with the most common source being contaminated water. Some strains can cause fever and dysentery, and in some rarer cases strains of *E. coli* can cause persistent diarrhea in young children and have hemolytic properties. The strain O157:H7 can also cause kidney failure (USEPA, 2002b). There have been two-reported contamination incidents possibly associated with backflow. In 2000 in Medina County, OH, there were two gastroenteritis due to outbreaks of *E. coli* and approximately 30 became ill (*Cleveland Plain Dealer*, 2001).
- *Salmonella* are one of the primary intestinal bacterial waterborne pathogens resulting in typhoid fever or gastroenteritis (salmonellosis) (Benenson, 1995), and septicemia (USEPA, 2002b). The symptoms of the gastrointestinal disease caused by *Salmonella enteritidis*, include fever, abdominal cramps, and diarrhea, usually beginning within 12 to 72 hours. The diarrhea can be severe, and the person may be ill enough to require hospitalization (CDC DBMD, 2001). The one incident of salmonellosis reported in the United States was in 1983 in Richland, WA, where 750 became ill with *Salmonella enteritidi*. The incident involved new plumbing and contaminated ice (CDC, 1984).
- *Campylobacter jejuni* is an avian gut bacterium that is the primary cause of bacterial diarrhea in the United States (CDC, 2002b). Some estimates are that it infects over 2 million people per year, but only 10,000 cases are reported annually. It is primarily a

food borne pathogen, but has also been implicated in waterborne outbreaks (CDC, 1996). In Noble, OK, in 1986, 250 people became ill with diarrhea due to infection from *Campylobacter* (CDC, 1996).

- Cyanobacteria are photosynthetic free-living bacteria that produce blooms in fresh water. The cyanobacterial toxins can produce acute neurotoxicity, hepatotoxicity, gastroenteritis, respiratory ailments, skin irritation, and allergic reactions through contact or ingestion (CDC, 2002c). An outbreak occurred in 1992 in Ritzville, Washington, when backsiphonage occurred from a drain sump near a new reservoir, which caused a reoccurring contamination of Cyanobacteria (AWWA PNWS, 1995).
- Norwalk and Norwalk-like viruses are a family of viruses that cause viral gastroenteritis with vomiting, diarrhea, upper respiratory problems, and fever (USEPA, 2002b). Humans can develop immunity to these viruses, but this is not permanent and re-infection can occur (USFDA, 2001b). In 1980 in Lindale, GA, 1500 people became ill with a Norwalk-like acute gastrointestinal illness because of a contamination incident for which the specific chemical or microbiological contaminant was never determined (CDC, 1982).
- *Giardia lamblia* is an intestinal protozoan parasite that exists in natural waters in a non-reproductive stage (cysts), which can cause diarrhea, vomiting, cramps, and bloating (USEPA, 2002b). The infection is passed through fecally contaminated food or water. It is usually self-limiting, but can lead to chronic diarrhea, anemia, fever, and death among kids, elderly, and the immunocompromised (Hoxie et al, 1997; USEPA, 1998; CDC, 2002a). Giardiasis has been reported in 12 incidents that were possibly caused by backflow. In 1979, 2,000 illnesses were caused after backpressure

effluent from a tree bubbler system in an Arizona State Park (Lake Havasu) contaminated the potable water supply (USC FCCCHR, 1993). In 1994, dozens of people became ill from *Giardia lamblia* contamination through a cross-connection between a drain and an ice machine at a convention in Columbus, Ohio (AWWA PNWS, 1995).

- *Cryptosporidium parvum* is usually very underreported, with one study estimating that only three out of 10,000 infections are reported. Thus surveillance for detected cases of a reportable illness may substantially underestimate rates of infection and morbidity (Perz, Ennever, and LeBlancq, 1998).

2.5 Evaluation of Possible Waterborne Contaminant

Creation of a waterborne disease through the intentional introduction of biological agent would be a legitimate method of attack. There has been little work done on the feasibility of using chemical or biological agents through a waterborne route (Burrows, 1998; Burrows and Renner, 1999), though there have been reports ranking the biological agents that could be used in such an attack. For instance, one confidential report completed a threat analysis based on the following categories: health effects of the agent, latency, persistence in water supply, ease of dissemination, ease of obtaining or making agent, thereat to saboteur, and use of agent as a water agent. These values were then used to calculate the threat index:

$$\text{Threat index (TI)} = [H^2]\,[L]\,[P^3]\,[ED^2]\,[EP^2]\,[TS]\,[WT]$$

Each of the variables was given a score of one to five for each contaminant. Based on this scoring, *Cryptosporidium parvum* received the highest ranking (Confidential Report #1). The report found that chlorine resistant microbiological agents (*Bacillus anthracis*

spores and *Cryptosporidium parvum* oocysts) can pose a significant threat to water supplies (Confidential Report #1). In another study of possible biological contaminants that could be used in an attack on the water system, Burrows and Renner listed *Cryptosporidium parvum* as a possible agent. They stated that it is unknown if the protozoan has been weaponized, but that it is a definite water threat that is stable in water for days, with the oocyst being chlorine resistant. Note that they define chlorine tolerance as in the ambient temperature, < or = to free available chlorine, surviving more than 30 minutes (Burrows and Renner, 1999).

Several different scenarios for attack were also analyzed. It concluded that the use of *Cryptosporidium parvum* to intentionally contaminate unfiltered water supplies can create illnesses and a potentially significant number of deaths for those immuno-compromised (Confidential Report #1). The report also concluded that it would be difficult to impact a large city using filtration, but medium and small-sized cities could potentially be impacted even if they use filtration at their treatment plants. Another feasible method of attack would be to contaminate a distribution system using backflow. Smaller scale attacks on high value targets could also be possible unless filtration is used within those buildings. A saboteur with knowledge of the system and using a model, could inject *Cryptosporidium parvum* at strategic points in the system and could cause widespread illnesses and deaths among the immunocompromised (Confidential Report #1).

Based on this information, *Cryptosporidium parvum* would be a legitimate biological weapon for dispersal into a water system. Background of this agent helps explain why it would make such a good agent. The species *Cryptosporidium parvum* is a

coccidial protozoan parasite (Hunter, 1997) found in the intestines of many birds and mammals (Prescott, Harley, and Klein, 2002). Tyzzer first described the morphology and life cycle in 1912 (AWWA, 1999b). It remained somewhat obscure until 1971 when it was found to be associated with bovine diarrhea. In 1976, two independent groups reported the first cases of human cryptosporidiosis. In 1984, the first waterborne outbreak was reported (AWWA, 1999b). The organism is in the suborder *Eimeriorina* and family *Cryptosporidiidae*. This suborder also contains *Isospora belli* and *Toxoplasma gondii* (AWWA, 1999b).

In the stage when it is transmissible, *Cryptosporidium parvum* is a thick-walled oocyst approximately 4 to 6 μm in size (AWWA, 1999b). When the oocyst is ingested, the cyst membrane opens (called excystation) in the small intestines, which releases four sporozoites (AWWA, 1999b; Hunter, 1997). These attach to and invade the epithelial cells of the gastrointestinal tract, where they are taken into superficial parasitophorous vacuoles (AWWA, 1999b; Hunter, 1997). The excystation phase usually requires reducing conditions, pancreatic enzymes, and bile salts; however, it may occur in warm aqueous solutions without any special stimuli (AWWA, 1999b). Sporozoites that have penetrated enterocytes develop into trophozoites, which is a stage in which they divide asexually forming meront stages containing merozoites (AWWA, 1999b; Hunter, 1997). These merozoites can infect other cells or they can produce stages that begin the sexual cycle. These merozoites also infect other epithelial cells, which increases the infection (Hunter, 1997). Some merozoites will form microgametes and macrogametes. These microgametes fertilize the macrogametes, which then become zygotes. Approximately 20 percent of the zygotes mature into oocysts, which are then surrounded by a protective

wall to ensure their survival (Hunter, 1997). The oocysts are released in feces and they can infect other hosts (AWWA, 1999b). This entire life cycle can be completed in a single host (Hunter, 1997). These are autoinfective life cycle forms that can maintain the parasite life cycle in the host. It is believed that this stage and the type I meronts are largely responsible for the continuation of the life-threatening disease found in immunodeficient people who have not had repeated exposure to environmentally resistant forms (AWWA, 1999b).

The oral infective dose ranges from 132 ingested viable oocysts (Roefer, Monscvitz, and Rexing, 1996) to 239 (Haas et al, 1996). It is possible that the dose is as low as 30 (DuPont et al, 1995) or even down to 10 (Confidential Report #1). The disease has an incubation period of five to 28 days, with a mean of 7.2 days. The duration varies according to the immune status of the host (AWWA, 1999b). The main clinical feature is diarrhea, with severity varying from patient to patient (Hunter, 1997). Other symptoms can include abdominal pain, nausea, fever, and fatigue (AWWA, 1999b). The symptoms last from two to 26 days, but can be longer, sometimes for several months or even until death (Hunter, 1997). *C. parvum* is now the most common cause of diarrhea throughout the world (Hunter, 1997). It can be life threatening to those immunocompromised individuals (AWWA, 1999b), though lethality is usually low (Confidential Report #1). There is no curative therapy for cryptosporidiosis—management is supportive if necessary (Hunter, 1997). Contaminated water is the largest potential common source of transmission, but close personal contact is another important source of transmission. This includes person-to-person contact between family members, health-care personnel, day-care employees, etc. Another route is animal-to-person, which

can include pets. Reservoirs of the agent include all mammal species, with the young of most animals especially prone (AWWA, 1999b).

Cryptosporidium parvum would be a dangerous contaminant based on its oocyst. The oocyst is very resistant to environmental elements as long as its thick two-layered wall is intact. The oocyst can survive for months in cold aquatic environments (lakes and streams) and it can remain viable and infective even after freezing at –15° C for eight to 24 hours. It takes a great deal to inactivate the spore, requiring exposure to a temperature of 64.2 deg C or higher for longer that two minutes. The oocyst is also susceptible to drying at 18 to 28 deg C for more than four hours (AWWA, 1999b). The oocysts are also highly resistant to chlorine-based disinfection (Schaub et al, 1993). Ct values of 9,000 mg-min/L are required to inactive the oocysts; however, UV light can achieve removals at greater that 4 log rates (Confidential Report #1). There are methods to remove the contaminant form water. Properly designed and operational granular filters using proper pretreatment can effectively reduce the oocysts in drinking water sources (LeChevallier and Norton, 1995). Conventional surface water treatment using coagulation and filtration will remove from 99 to 99.9% of the oocysts, and they are essentially 100% removed through reverse osmosis treatment (Confidential Report #1).

Because of this hardiness, the species can be found in many different places. For instance, 11 samples in six rivers in the western U.S. were found to contain the oocyst, with results ranging from two to 112 oocysts per liter (Ongerth and Stibbs, 1987). In another large study of water through the western U.S., oocysts were found in 75% of lakes and reservoirs, 77% of rivers, and 91% of both raw and treated sewage (Rose,

1988). Another similar study in the eastern U.S. found oocysts in 87% of river water (LeChevallier, Norton, and Lee, 1991).

Some outbreaks are often unrecognized (AWWA, 1999b). Even with the illness being unrecognized, those cases that were reported made it the most commonly identified cause of waterborne disease in 1993 and the second in 1991 and 1992 (AWWA, 1999c). The disease was first documented in the U.S. in 1984 in Texas (AWWA, 1999b; D'Antonio et al, 1985). The water supply for the town was unfiltered artesian well water that was chlorinated. Analyses of the well water showed that it contained fecal coliforms because of contamination with the town's sewage (D'Antonio et al, 1985). Since 1984, the disease has occurred in water systems using well and spring water treated solely by chlorination and in filtered surface water systems.

The outbreak in Georgia occurred from January 12 to February 7, 1987, and infected an estimated 13,000 people out of 64,900 served by the system. The actual number was estimated by extrapolating the results of a telephone survey. The water source was a river, and treatment included coagulation, sedimentation, and rapid sand filtration. It was later determined that a sewage overflow was draining into the river immediately above the treatment plant, which was not working properly—mechanical flocculators were not working; filtration was poor because of lack of control, and filters were not being backwashed (Hayes et al, 1989).

The outbreak in Swindon and Oxfordshire, UK, was one of the largest recorded outbreaks in Europe. It was estimated that 34% of the taps tested positive with levels ranging from 0.002-24 oocysts per liter. The water was treated through flocculation, rapid sand filtration, and chlorination. The cause was never determined, but it may have

built up in the sand filters by backwashing and reusing the backwash to such an extent that breakthrough occurred (Richardson et al, 1991).

From January to February 1991, another outbreak occurred in south London infecting 44 people. Oocysts were not identified in any samples, but the illness was associated with drinking more than one glass of water per day. The water supply was treated through slow sand and dual filtration, but no obvious defects or operating problem were identified (Maguire et al, 1995). Another outbreak occurred in Bradford, England (Atherton, Newman, and Casemore, 1995). Drinking water from the suspect supply was associated with the increased risk. *Cryptosporidium parvum* oocysts were detected early in the outbreak from the supply system. After heavy rainfall, turbidity levels increased but no other abnormality was found (Atherton, Newman, and Casemore, 1995).

Probably the largest outbreak ever occurred in Milwaukee in the spring of 1993. There were 739 confirmed cases, but phone surveys later showed that up to 30% in the area served also had symptoms, which meant that approximately 403,000 people were infected (MacKenzie et al, 1994). There were at least 111 fatalities (Confidential Report #1). The infection rates varied by water zones throughout the city. Oocysts were found to be in concentrations from 6.7 to 13.2 per 100 liters in ice made from the water (MacKenzie et al, 1994). The water was treated using chlorine and polyaluminium chloride coagulations, mechanical flocculation, sedimentation, and rapid sand filtration. The filters were backwashed and the backwash water was reused. No specific failure was identified, but higher than normal turbidity readings were noticed at the beginning of the outbreak (MacKenzie et al, 1994).

Hunter found that of 11 outbreaks, three were associated with unfiltered well water and four occurred after unusually high rainfalls. Five utilities reported increases in water turbidity before the outbreak, most of which were within the prescribed limits. However, turbidity remains one of the easiest and most useful routine water quality indicators (Hunter, 1997).

The literature shows that *Cryptosporidium parvum* oocysts could be a legitimate choice for sabotaging a water system. If this were used, the amount that could be produced would be an important issue. The amount can only be estimated on available information. For instance, it has been estimated that one infected calf can produce up to 50×10^9 oocysts in one week (Confidential Report #1). This level was extrapolated into the total amount of oocysts that could be produced in a specific period of time. Based on this estimation, it would be feasible for a saboteur to produce 0.4 kg of oocysts (equating to 80 calf weeks of production). Using the same estimate, it would be difficult to produce 4 kg (800 calf weeks) and very difficult to produce 40 kg (8,000 calf weeks) (Confidential Report #1). These may not seem like a large quantity of oocysts, but it would not take a great amount to produce a large impact. If it is assumed that a dose of 10 oocysts will cause illness, then one mL of purified oocysts would contain enough to cause 1.3×10^9 illnesses (Confidential Report #2). If the infective dose is assumed to be 132 oocysts, then one mL would have 9.8×10^7 infective doses (Confidential Report #2). Another estimation of the impact was completed to determine the volume of purified material that would be required to achieve one ID_{50} per liter in 1 billion gallons of water. If the infective dose were 10 oocysts, then it would take less than 3 mL of purified substance to contaminant 1 billion gallons. If the infective does is 132 oocysts, then the

amount is less than 40 mL (Confidential Report #2). This shows how little of the oocyst is required to contaminant a rather large quantity of water.

2.6 Past System Sampling

Past sampling and guidance on sampling has been inadequate. Frequency has been based on the size of the population served and is normally spaced over time. The government does not provide any procedures for achieving the goal of representative sampling in distribution system (Lee and Deininger, 1992). Monitoring within the system has historically been based on regulatory requirements for total coliform sampling. There is little other information about the system. The EPA regulations for system monitoring are designed only to show catastrophic failures and not the on-set of a problem, but may provide some sort of early detection (AWWA, 1999b). Sampling is very limited, and only gets worse for smaller systems where monitoring is almost non-existent. A limited number of chemicals are monitored, but these are not tested routinely enough. Usually when such an incident occurs, it will only be detected if customers notice an irregularity in their water supply, and they will not be detected at all unless the contaminant can be detected through taste, odor, or color (Hoxie et al, 1997).

Coliform sampling can be an important water quality indicator, but most of the contaminants that could be used for attack would not be detected through this monitoring (USEPA, 2001). Analysis of several outbreaks caused by protozoa showed that the total coliform maximum contaminant level was not exceeded by any of the community water systems reporting outbreaks of cryptosporidiosis (Craun, 1994). Others have reported that coliform sampling has provided some useful data in that past in predicting waterborne infections. From 1993 to 1996, water quality data were available for 35 of 37

waterborne outbreaks with suspected infectious causes of disease. Coliforms were detected in 11 of the 12 outbreaks of bacterial or unknown causes of disease, but in only 5 of the 9 protozoan outbreaks (Karmer et al, 1996). From 1983 to 1992, coliform bacteria were detected in only half of the outbreaks and caused maximum contaminant levels violations in only one fourth of public water systems in the 3 to 12 months before an outbreak (Craun, Berger, Calderon, 1997). Obviously coliform sampling is not adequate for all types of contaminants, and based only on the microbiological contaminants, additional sampling is needed. The absence of coliforms does not mean the *Cryptosporidium parvum* are not present, especially in systems that use disinfectant, because *Cryptosporidium parvum* is much more resistant to disinfectants (Moore et al, 1994).

Additional monitoring beyond those minimum requirements may provide some sort of early detection (AWWA, 1999c). Site selection for coliform monitoring should address geographical coverage, detention time, and accessibility and should include the entire distribution system (AWWA, 1999c). Routine analysis of heteotrophic plate counts is a relatively inexpensive water measurement tool that can be used to understand water quality changes within the system. To be useful though, a baseline must be established at the sites sampled. Some utilities have used a 1-log or set percentage increase to indicate actions required. If nothing else, HPCs can indicate when flushing is required (AWWA, 1999c).

There are specific sampling methods for *Cryptosporidium parvum.* Those specified by the Information Collection Rule require that large water volumes be concentrated and the retentate be eluted and then concentrated by centrifugation.

Following that, pelleted materials are separated from debris by flotation on an ercol sucrose gradient. A portion of this material is placed on a membrane filter and stained with fluorescent antibody (AWWA, 1999b).

The oocysts are confirmed by size, shape, and internal morphological characteristics. Method 1622, direct immunomagnetic separation technology, selectively removes oocyst from other particulates in sample. Recovered parasites are then stained using fluorescent antibodies with confirmation through fluorescent stain. Other detection techniques are in development, including fluorescence-activated cell sorting (FACS) coupled with fluorescent in situ hybridization (FISH) (AWWA, 1999b), but these do not provide results quickly. Hunter notes that some of the traditional methods only detect approximately 9% of the oocysts (Hunter, 1997).

Most of these detection methods listed above can take a large amount of water and a long period of time. AWWA recommends that continuous optimization performance for turbidity and particle removal be implemented to ensure effective treatment at plants. Turbidity in the effluent water should be 0.1 ntu or less. AWWA also noted that when filter effluent turbidity was between 0.1 and 0.3 ntu, *Cryptosporidium parvum* presence was as much as 90 percent greater than when filter effluent turbidity was 0.1 ntu or less (AWWA, 1999b). This, as well as the increases seen in turbidity for many of the outbreaks, shows that turbidity can be an important parameter for measuring *Cryptosporidium parvum*.

2.7 Security Responses

There are several responses that could be done to not only limit the impact but also to correct the system after an attack. The first item is to eliminate a threat. There

are security measures that can be taken to help minimize the risk. The first measure is to maintain a significant disinfectant residual. There is more information known about chlorine's specific agents, but not as much is known about chloramines. Other actions that can be taken include physical security items such as increased security around key facilities in the system as well as installation of secure backflow preventers or check valves around key facilities in the water system. If the backflow preventers are to be affected, they must be installed so they cannot be disengaged easily. There should also be an early warning system for the raw water supply that is able to detect contaminants that may be introduced into the system. Additionally, continuous monitors at key locations within the system should be installed. To be effective, these monitors should either sample continuously or very frequently at these key locations. The results from both the distribution system and the raw water supply should be relayed back to a central operation center. And lastly, a detailed emergency response should be developed (Haested Press, 2003). Some of these actions are discussed more in-depth below.

There are several recommendations to control contaminants in the source water. The most absolute barrier is closure of water intakes and use of alternate sources; however, this is only effective if the contamination is discovered prior to the water entering the treatment plant. Another possibility is cleanup of spills prior to intakes. This is limited to specific contaminants such as oils. There are also enhanced temporary chemical treatments that can be done at the plant. In order for this to occur, the exact chemical nature of the contaminant must be known (Haested Press, 2003).

Another measure of protection is the disinfectant residual. Chlorine residuals of approximately 0.5 mg/L free chlorine should be maintained in the system, but should be

increased if there is a perceived threat. It is possible to deactivate the chlorine by adding sodium thiosulfate, but this would require large amounts and a reliable injection system (Clark and Deininger, 2001).

The next step is to deal with contamination when it is in the system, which is much more severe for several reasons. Once the contamination is within the system, the disinfectant is the only barrier. Additionally, monitoring within the system is limited. Travel time in the system from one customer to another can be very short, and if it is not detected, then the contaminant can reach many customers over an extended period of time (Haested Press, 2003).

If all the corrective measures fail, the best solution may be isolation of the contaminated area. This was done in 1982 in a Connecticut gas leak that was isolated, the residents evacuated, and area sealed (AWWA PNWS, 1995). There are cases when the area cannot be isolated, such as an incident that occurred in Charlotte-Mecklenburg, where 90 million gallons were required to flush the system (ABPA, 1999).

When there is some type of system contamination, the system will usually need to be flushed, but sometimes contaminants may not be adequately removed by flushing. This may be the case with microbiological contaminants that may concentrate in biofilms and then may not be adequately removed by flushing. For example, the city of Muncie, Indiana, drained its entire system over a weekend to remove the biofilm, but the efforts were unsuccessful (Geldreich, 1996). Other contaminants may adsorb to the biofilm or corrode the pipe and thus be released slowly back into the system, thus requiring an unreasonable amount of time to flush them from the system (USEPA, 1992). Sometimes

the system may need to be physically cleaned. Jetting and sandblasting can also be used to remove such layers.

Sometimes pipe replacement is the only option. An example of this situation could be when a chemical absorbs to pipes and then is slowly released, as chlordane will do to even clean pipes. This occurred in 1987 in Fairlawn and Hawthorn, New Jersey, when the pesticides chlordane and heptachlor were introduced into the distribution system and the affected lines were removed and replaced (AWWA PNWS, 1995). This could also be the case if radioactive material would be placed in the pipe, because it can be very difficult to physically remove.

2.8 Examples of Model Applications

One tool that is used to a large extent in water distribution systems that have yet to be used widely for security specific applications are water distribution models. Models have been used to determine the changes that occur within the distribution system, including contamination, but this has not been applied to intentional contamination to a large extent. .

One example of how modeling could be used for a security specific scenario includes the following scenario as depicted by Haestad Press. The police call the water utility with information concerning a possible water contamination. The location, chemical, time, and duration are known. The first action is to notify the public. The second action is to determine how to flush the contaminant, i.e., which hydrants to open and for how long. Flushing can drastically change the way water moves throughout the system and trial-and-error would be very long and risky. The best method is to use a model to analyze the flushing, and this will also be the easiest. The problem with this is

that the model must be calibrated for a wide range of possibilities and ready to apply very quickly in the extended period mode. The model must be set-up in automated mode so that operation is represented by series of logical controls established for the current operating procedures. The authors state that such an evaluation is possible, including the required data, but that only limited demonstrations of this type of operation have been accomplished so far. The obvious key to this is that the model must be ready immediately because there would not be time to establish the model in an emergency (Haested Press, 2003).

Past water distribution system modeling has been conducted on a variety of contaminants, including volatile organic compounds, inorganic chemicals, and microbes, as well as disinfectant decay (Haestad Press, 2003). Models have been completed in forensic studies, also called hindcasting, to identify responsible parties in litigation. Many of these have been completed, but few have been published because of legal issues (Haested Press, 2003). Models used to predict microbial behavior in water system are not routine because of the complexity of microbial interactions and lack of overall information about the ecology in drinking water (LeChevallier, 1991). Some examples of modeling are discussed below.

The usefulness of modeling to predict contaminant propagation was shown by Clark, et al (1988). More recently, modeling has been used to track the incidence of disease-causing contamination to its source (Clark et al, 1996). The EPA used water modeling to study a salmonella outbreak in Gideon, Missouri, that began in November 1993. Gideon had 1,104 residents, and it was estimated that up to 44% (over 600) of the residents were infected with diarrhea, and seven nursing home residents died (Rossman,

Clark, and Grayman, 1994). By the time it was recognized as a water outbreak, none of the routine surveillance samples yielded positive samples. This illustrated the difficulty of tracking and identifying the course of contamination in drinking water systems (Clark and Deininger, 2001). Epidemiology studies showed that no similar food source was shared, but they all drank the same water (Clark et al, 1996). Using a model called EPANET, it was concluded that bird droppings within a water storage tank were most likely the source of contamination (Rossman, Clark, and Grayman, 1994). The model was used to develop various scenarios for the contaminant transport as well as chlorine residuals after the outbreak. The water was drawn from two adjacent deep wells (396m) and was not chlorinated (Clark et al, 1996). There was also a sudden drop in temp on November 9, 1993, causing a turnover of water in the tank. This likely caused contaminated water to mix with the clean water (Clark et al, 1996).

Other similar studies have been completed. The EPA modeled the water system in Cabool, MO, where an *E. coli* O157:H7 outbreak occurred. The outbreak involved 243 cases and 6 deaths. It was attributed to two water main breaks (Geldreich, 1996). One of the first modeling examples found in the literature was completed at the North Penn Water Authority. This study, conducted by the EPA and North Penn Water Authority, used a series of field monitoring and systems to study contaminant movement within the system (Clark, Grayman, and Males, 1988). The "Solver" component of EPA's Water Supply Simulation Model (WSSM) was applied to the steady-state hydraulic solution using the known concentrations in the water sources. The actual pathways of water flow and trace analysis was conducted. The major finding of the study was the importance of adequate modeling of the system matching the actual system, i.e.,

model calibration. Additionally, the study showed that water can change in quality before reaching the user, based on chemical or biological transformations or due to a loss of system integrity. Once calibrated, the steady-state predictive model was found to be a reasonable first step to characterize the system, but that general trends that are established must be verified through field sampling (Clark, Grayman, and Males, 1988). In that article, the authors evaluated results from a steady-state model to examine the actual pathways of water flow and time of passage and percentage of water that flows from a given source to a given node in a system. The major finding was the importance of adequately hydraulic modeling of the systems being studied and the importance of field studies in verifying systems performance (Clark, Grayman, and Males, 1988).

Another study, completed in Cheshire, CT, was done mainly for tank and system operation and design. The study found that tank operations can have a major impact on drinking water—long residence time in tanks implies that chlorine residual can be very low or zero for the discharge. The chlorine residuals, based on the assumptions, will vary widely depending on the location of the sampling point and operating scenarios, with the ranges being from 0 to 2 mg/L. These residuals varied throughout the day; however, they did note that changing the tanks operations did not solve the problem. Additionally, although it was very difficult to characterize the water in the system, the authors did find that field data showed what the model predicted, thus models can be very useful (Clark, Grayman, Males, 1993).

Another study, conducted with the South Central Connecticut Regional Water Authority, used a contaminant propagation model that demonstrated long residence times in one of the service areas. The result of the study showed the potential difficulties in

maintaining chlorine residuals. A follow-up study verified that maintaining a chlorine residual is difficult and demonstrated that a first order decay model associated with modeling chlorine is inadequate (Clark et al, 1994).

Forensic models are done to show what occurred in the past. These are not discussed in detail here for two reasons. First, not many of these have been published due to legal issues (Haested Press, 2003). And second, the focus of this thesis is to help avoid such a scenario, that is, where contamination has already occurred and studies must be conducted to verify the spread. However, discussion of these do show how modeling can be accomplished. One of the most famous cases of forensic modeling occurred in Woburn, MA. A model there was used to substantiate the contamination that occurred many years before (Murphy, 1991; Harr, 1995). This contamination was the subject of the book and movie "A Civil Action". The model done was for groundwater contamination requiring years of historical data (Haestad Press, 2003). Another similar study was conducted for in Dover Township, NJ, where models were developed there for the time period from 1962 to 1996 to determine the path of water (ATSDR, 2001; Maslia et al, 2000).

Another forensic study was completed in Phoenix and Scottsdale, AZ, as part of litigation over contamination of wells first detected in the fall of 1981 (Walski and Harding, 1997a and 1997b). The primary contaminant was trichloroethylene (TCE). The analysis was done using a modified version of EPANET (Rossman, Clark, and Grayman, 1994) The results of the study showed that concentrations can fluctuate widely at specific locations both hourly and seasonally, due to pumping changes based on varying demands (Harding and Walski, 2000).

These examples show how models can be used in a wide variety of scenarios to determine how contamination impacts the distribution system. Similar modeling efforts have not been completed for intentional contamination. Because these have not been used for these types of contamination scenarios, there is little guidance for this modeling application. Coupling this modeling use with a potential agent could provide very useful information that could help water utilities prepare for responding to contamination scenarios.

CHAPTER 3. RESEARCH OBJECTIVES

3.1 Primary Goals

The primary goals of this study are:

- Develop guidance for utilization of water distribution modeling software for security related issues.
- Demonstrate the use of hydraulic distribution system models for drinking water security issues.
- Select an appropriate microbiological contaminant that poses a risk to water security distribution systems and analyze methods to detect the contaminant, using normally measured water quality parameters.
- Apply modeling guidance to the detection of the microbiological contaminant.

3.2 Major Objectives

The major objectives of this study are:

- Provide guidance on model use for security related applications, for all sizes of water utilities. Guidance will include data inputs, outputs, decision points, site-specific information required, risk assessment techniques, and possible responses.
- Provide database of all available distribution system hydraulic models.
- Provide case studies of how water models have been used for water security.
- Identify one microbiological contaminant that would present a significant risk to drinking water systems from intentional acts of contamination.

- Calculate the aqueous concentration of the contaminant that would present an infective does from oral consumption.
- Determine the relationship between concentrations of this contaminant and changes in standard measurements of drinking water parameters (turbidity, chlorine decay, TOC, pH, and conductivity).
- Evaluate the detectability based on 3σ changes in these parameters.
- Determine, through the use of models, if the contaminant is detectable based on a limited number of sensors in the distribution system.
- Determine if routine, off-the-shelf, point of entry detection equipment will detect the contaminants at a low enough concentration.

CHAPTER 4. MATERIALS AND METHODS: MODELING GUIDANCE

4.1 Description of Models

Models have evolved tremendously to meet water system requirements. In the 1980s, increasingly sophisticated codes were developed, which included stand-alone water quality models (Males et al, 1985; Clark, Males, and Stevie, 1984). In the late 1980s, the first models able to simulate time-varying conditions were developed (Grayman, Clark and Males, 1988; Clark, Grayman, Males, and Coyle, 1986). Fully dynamic models and models that account for dispersion have since been developed (Axworthy and Karney, 1996; Islam and Chaudry, 1998). For the last decade, the attention has been focused on algorithms for use in modeling the water quality in piped systems (Boulos et al, 1994). Based on this, modeling water quality in water distribution systems has become a widely accepted tool in support of water supply planning, operations and research.

Models can be used in a wide range of situations. Even when it is not possible to accurately model behavior of a chemical or a microbe, models can provide a picture of how water moves throughout the distribution system. From this information, it can be determined which portions of the system are exposed to water from particular sources, tanks, or waterline breaks (Haested Press, 2003).

One of the emerging abilities of models is to help utilities understand how the system will respond due to either accidental or intentional contamination (Haested Press,

2003). Extended period simulation models can be extremely effective in examining consequences of "what if" scenarios. Specifically, as applied to water system security, models have been used to examine three different time frames. First, they have been used as planning tools to assess vulnerabilities of the systems for various events. Second, they are used as a real-time tool during actual events for assistance in formulating responses. Third, they have been used for investigating events that occurred in the past (Haested Press, 2003).

There are of course limitations to using models. Flow patterns in a water distribution system can be highly variable and these flows can have a significant impact on the way contaminants are dispersed in a network, thus it is difficult to predict where a parcel of water will be at a given time (Clark and Deininger, 2001). However, if a model is calibrated properly, these limitations can be minimized.

Hydraulic models can perform evaluations using two different time patterns: steady-state (system is not changing) or extended period simulation (many different steady-state models run together). The steady-state analysis computes the state of the system by assuming the hydraulic demands and boundary conditions do not change. These computations include flows, pressures, pump operating valves, positions of valves, etc. The information typically obtained from such a model includes pressures and equilibrium flows (Haested Press, 2003). Steady-state models can be a reasonable first step to characterize the distribution of water quality in multi-source systems, but are less dynamic in terms of operation (Clark, Grayman, and Males, 1988). Steady-state models are basically a snapshot in time and used to determine the operating behavior of the system under static conditions. These models can be useful in determining the short-term

effect of fire flows or average demand conditions within the system (Haested Press, 2003) as well as modeling flow-tracing for contaminant movement, flow paths, and travel times through the network (Clark, Rossman, and Wymer, 1995).

Because water systems are rarely in a steady-state, these models are somewhat limited. Their use is like looking at a blurred photograph of a moving object. Because of this, they are typically building blocks for other types of simulations or done to analyze specific worst-case conditions such as fire demand, peak demands, and other system component failures that do not have a large impact by time (Haested Press, 2003).

Dynamic water quality models, or expanded period simulation (EPS), are used to simulate movement and transport of substances in water under time-varying conditions (Clark, Rossman, and Wymer, 1995). They can be very effective for contaminant propagation studies. When combined with a flow-tracing algorithm, EPS models have proven to be very effective in modeling contaminant propagation in the drinking-water distribution system (Clark, Grayman, Males, 1993). These model changes in water tank levels, valve settings, storage tanks and pumps going on and off-line, flow reversal, and rapid demand changes (Boulos et al, 1994). For these reasons, dynamic models have largely replaced steady-state models for water systems because they provide a better representation of the time-variant behavior of contaminants in distribution networks, particularly that arising from flow reversal in pipes.

Dynamic models involve a sequence of steady-state solutions linked by an integration scheme for the differential equation describing the storage tank dynamics (Boulos et al, 1994). Put another way, these calculations are a series of steady-state model simulations tied together in sequence. After each steady-state step, the system

boundary conditions are reevaluated and updated to reflect those changes in the junctions. These steps continue until the end of the simulation (Haested Press, 2003).

The time period for these models has generally been limited to periods of a day or a few days; however, longer time periods can also be completed. Longer time periods, up to weeks, months, or even years, can be completed with only minimal changes to the model codes (Haestad Press, 2003). The data requirements for these models are much greater than for steady-state models. This data includes water use patterns, more detailed tank information, and operational rules for pumps and valves. Additional information required includes start time, duration, and the hydraulic time step (Haestad Press, 2002).

4.2 Water Quality Analysis Algorithms

The water quality portions of many water quality models (H2OMAP, WaterCAD, PipelineNet, WADISO SA, Mike NET, Pipe 2000, etc.) are based on the conservation of mass with incorporation of reaction kinetics as calculated in EPANET. The basic equations used in these models are described below (Rossman, Boulos, and Altman, 1993; Rossman and Boulos, 1996). The programs are based on the fact that a dissolved substance will travel in the pipe with the same velocity as the fluid in the pipe and at the same time it will react with its concentration either increasing or decaying. In most pipe systems, there is little longitudinal dispersion, i.e., there is no intermixing of mass between adjacent parcels of water that are traveling down the pipe (Rossman, 2000).

Advective transport in the pipe is represented by the following equation (Rossman, 2000):

$$\frac{\partial C_i}{\partial t} = -u_i \frac{\partial C_i}{\partial x} + r(C_i)$$

where:

- C_i = concentration (mass/volume) in pipe i as a function of distance x and time t
- u_i = flow velocity (length/time) in pipe i
- r = rate of reaction (mass/volume/time) as a function of concentration.

Where two or more pipes meet, the incoming flow is assumed to be mixed completely and instantaneously. This allows the substance concentration to be calculated through a flow-weighted sum of the concentrations from the in-flowing pipes by the following equation (Rossman, 2000):

$$C_{i|x=0} = \frac{\sum_{j\in I_k} Q_j C_{j|x=L_j} + Q_{k,ext} C_{k,ext}}{\sum_{j\in I_k} Q_j + Q_{k,ext}}$$

where:

- i = link with flow leaving node k,
- I_k = set of links with flow into k,
- L_j = length of link j,
- Q_j = flow (volume/time) in link j,
- $Q_{k,ext}$ = external source flow entering the network at node k,
- $C_{k,ext}$ = concentration of the external flow entering at node k.
- The notation $C_{i|x=0}$ represents the concentration at the start of link i, while $C_{i|x=L}$ is the concentration at the end of the link.

The easiest method to deal with storage facilities is to assume the contents are completely mixed. It is reasonable to make this assumption for many tanks that operate under fill-and-draw conditions assuming that there is enough momentum flux imparted to the inflow (Rossman and Grayman, 1999). When these are assumed, the concentration throughout the tank is a blend of the current contents and the entering water. However, at the same time, the internal concentration may be constantly changing because of reactions. Storage facilities can be represented by the following equation (Rossman, 2000):

$$\frac{\partial(V_s C_s)}{\partial t} = \sum_{i \in I_s} Q_i C_{i|x=L_i} - \sum_{j \in O_s} Q_j C_s + r(C_s)$$

where:

- V_s = volume in storage at time t,
- C_s = concentration within the storage facility,
- I_s = set of links providing flow into the facility,
- O_s = set of links withdrawing flow from the facility.

4.3 Analysis Algorithms

There are two basic methods used for solving the model equations, the Eulerian and Lagrangian approaches (Haested Press, 2003). The Eulerian approach is best described as an observer located at a fixed location watching the water as it flows by (Haested Press, 2003). This method was originally developed for water quality modeling in distribution systems (Grayman, Clark, Males, 1988) and was later formalized and named the Discrete Volume Method (Rossman, Boulos, and Altman, 1993).

The Lagrangian method is a hybrid of the Eulerian Discrete Volume Method (DVM) of Rossman, Boulos, and Altman (1993) and the Lagrangian Event-Driven Method (EDM) of Boulos et al (1994). This method is described as the observer moving with the flow rather than watching it. Rather than having a fixed grid, the parcels of water are tracked through the pipe. Each parcel of water has a homogeneous concentration and is tracked through the pipe. New parcels are added when the water quality changes due to source quality changes or parcels combining at the junctions (Haested Press, 2003). This method was developed by Liou and Kroon (1987) and Hart, Meader, and Chiang (1986), and is commonly used in water models today.

For the programs, the time steps are much shorter than the hydraulic time, which is done to accommodate the short travel times that can occur within the pipe (Haestad

Methods, 2002; Rossman, 2000). The method tracks the size and concentration of non-overlapping water segments that fill each link in the network. Throughout time, the upstream segment in a link increases in size as water enters. At the same time, there is an equal loss in size of the most downstream segment. The sizes of those in between remain the same. The contents of the segments are subjected to reactions and an accounting for total mass and flow volume entering nodes, as well as the contributions from external sources. The water positions are updated and new node concentrations are then calculated (Rossman, 2000).

4.4 Database of Distribution System Hydraulic Models

There are numerous models available, each with unique abilities in regards to not only hydraulic capacities but also applications in water security. These models are summarized in Table 4-1. A more in-depth description of these water models is provided in Appendix 1.

Each of the water models has some similarities. Hydraulically, all the water distribution models perform the same type of analyses: flow and velocity of water in pipes, pressure and head at nodes, height of water in tanks, discharge flows and pressures from pumps. They all perform steady-state and extended period simulation analysis. For water quality simulations, all perform age, trace analysis, and constituent analysis. Most use the same three common friction equations (Hazen-Williams, Darcy-Weisbach, or Manning's methods). Additionally, the programs have similar capabilities regarding modeling water quality. Additionally, they model constituents in the same manner: n-th order kinetics to model reactions in the bulk flow and zero or first order kinetics to model reactions at the pipe wall. Wall reaction rate coefficients can be correlated to pipe

Table 4-1 Summary of available distribution system hydraulic models.

Software	Water Quality Analysis	Security Specific
BRANCH 3.0 / LOOP 4.0	None	None
CROSS (WaterPac®)	Information not available	Information not available
EPANET (Version 2.0)	Water age, trace analysis, and constituent analysis. Constituent analysis various types of reaction coefficients to be input into the model.	Information not available
H_2OMAP/ H_2ONET	The program can conduct water age, trace, and constituent analysis. Constituent analysis various types of reaction coefficients to be input into the model.	Event/consequence management, vulnerability assessment, tracking contaminants to the originating sources, computation of purge volumes, event isolation, and customer report notification generation.
Helix delta-Q (Version 2.28)	Information not available	Includes "what-if" scenarios which allow closing pipes to view network effect.
InfoWater™ Protector	Same general capabilities as H_2OMAP/ H_2ONET	Models propagation and concentration of contaminants in system; assess effects of water treatment on the contaminant; evaluates potential impact of unforeseen facility breakdown. Locate areas of contamination and calculates population at risk. Identifies valves to close to isolate a contamination event. Tracks contaminants to the originating supply source, computes purging volume, flushing strategies, result on fire-fighting capabilities, and prepares data for eventual prosecution.
MIKE NET 2002	Water age, travel time, and constituent source tracking can also be performed. Tracks movement and fate of water quality constituents. Allows different reaction coefficients.	Allows "what if" scenarios, allowing user-selected changes in network configurations, demand loading conditions, and changes in physical system characteristics. Can run several different scenarios on the same network.
optiDesigner (Version 1)	Information not available	New update including stochastic behavior of the system and a method to determine the source of contamination. No release date has been set.
PIPE2000/KYPIPE (Version 2)	Automatic aging of pipes (roughness) and many other capabilities.	Information not available
PipelineNet	Water age, trace analysis, and constituent analysis. Constituent analysis various types of reaction coefficients to be input into the model.	Model flow and concentration of a biological or chemical agent within a city or municipal water system. Assesses effects of water treatment on the agent. Models flow and concentration of agent through the system and calculates population at risk.
Pipenet™	The program has "What-if" scenarios, but is advertised for broken or blocked pipes.	Information not available
STANET® (Version 7.3)	Stationary mixing/tracking of contents (heating value, water quality, water age).	None
WADISO SA (Version 4)	Water age, trace, and constituent analysis. Allows different reaction coefficients. Constituent analysis various types of reaction coefficients to be input into the model	Information not available
WaterCAD	Water age, trace, and constituent analysis. Allows different reaction coefficients. Constituent analysis various types of reaction coefficients to be input into the model	Includes scenario for selection of valves for contamination isolation and developing flushing strategies. Simulates failure of critical water sources and identification of customers who will be impacted by the event. Predicts influence of these events and assesses possible impacts of correction actions. Prioritizes physical security improvements using component criticality and water system safety.

roughness and the global reaction rates can be modified on a pipe-by-pipe basis. The constituents can grow or decay up to a limiting concentration. Also, they can perform four different models of tanks. These capabilities are explained more in-depth below.

4.4.1 Water Quality Simulations.

There are three water simulations that these models can complete: water age, source tracing, and chemical constituent.

Water age is a function that calculates the age of the water in the network, computed at any node. The models compute this characteristic based on EPANET calculations, which is performed under constant hydraulic conditions and is a simple, non-specific measure of the overall quality of delivered water. This analysis tracks the percent of water over time that reaches any node in the network from an original specified node. The specified node can be any node in the network. The information required for age analysis is pipe velocity and flow rate; therefore, no reaction coefficients are required (Haestad Methods, 2002).

The trace function determines the fraction of water that originates from a specified node over time, again with the calculations based on EPANET. EPANET treats the source node as a constant source of non-reacting constituent, entering the network at the node with a concentration of 100 (Rossman, 2000). The analysis can be useful for analyzing systems with two or more raw water sources, thus showing how the water is blended over time (Rossman, 2000). It can only be performed using the EPS method with input information of pipe velocity and flow rate (Haestad Methods, 2002).

The final water quality analysis is the chemical constituent. A constituent is defined as any substance for which the growth or decay can be adequately described through bulk and wall reaction coefficients (Haestad Methods, 2002). This type of analysis determines the concentration of the constituent at all nodes and links in the system. The constituent can be anything from chlorine to fluoride to an unwanted contaminant. This analysis determines the concentration of the constituent at all nodes and links in the system (Haestad Methods, 2002). The source of the constituent can be from the main treatment works, well head or satellite facility, or unwanted contaminant intrusion and either conservative or reactive species can be modeled.

This analysis can only be performed using the EPS. The following must be input into the model for chemical constituent:

- Initial Constituent: the initial concentration of the constituent at the beginning of the analysis.
- Bulk Reaction: reaction rate used to model reactions of the constituent within the bulk flow.

Wall Reaction: reaction rate constant for the material reacting along the pipe wall.

The constituent analysis is based on the principles of conservation of mass and reaction kinetics. There are three processes used to conduct this calculation (MWH Soft, Inc., 2002):

1. Advection in pipes. This is based on that fact that the constituent will travel down the pipe with the same average velocity as the fluid carrying it. While traveling, the constituent will react, either growing or decaying. Longitudinal

dispersion is usually not an important transport mechanism under most operating conditions meaning there is no intermixing of mass between adjacent parcels of water traveling down a pipe.

2. Mixing at Junctions. The mixing is assumed to be complete and instantaneous.
3. Mixing at Tanks. There are several different types of mixing in tanks. These different types of mixing are discussed under tank mixing.

4.4.2 Mode of Contaminant Entry

Another similarity between these distribution models is the mode of entry for the contaminant. The models allow any node in the system to serve as the source for a chemical constituent. Each modeling program allows several different methods to introduce the contaminant into the system. These are explained below (Haestad Methods, 2002; MWH Soft, Inc., 2002; Rossman, 2000).

- Concentration. This method fixes the concentration of any external inflow entering the system at a node. An example would be a reservoir or a negative demand located at a junction.
- Flow Paced Booster. This method adds a fixed concentration to the flow resulting from the mixing of all inflow to the node from other points in the network.
- Setpoint booster: This fixes the concentration of any flow leaving the node. This can be used as long as the concentration resulting from all inflow to the node is below the setpoint.
- Mass booster: This is used to add a fixed mass flow to the flow entering the node from other points in the network.

The best method to use for contaminant entry is discussed later. Note that there is one other method that can be used also. A separate tank and pump can be placed into the model. This will allow maximum control over the manner in which the contaminant is pumped into the system.

4.4.3 Tank Mixing

Tank mixing is another item that impacts the contaminant with the system. Again, the models complete this calculation based on EPANET methods, which includes complete mixing, two-compartment mixing, first in/first out plug flow, and last in/first out plug flow. These are described more in detail below.

- Completely Mixed. This assumes that all water entering the tank is completely and instantaneously mixed with the water already in the tank. This is a reasonable assumption for many tanks operating under fill-and-draw conditions providing sufficient momentum flux imparted to inflow (Rossman, 2000).
- Two-Compartment Mixing. This assumes that the tank storage is divided into two completely mixed compartments. Inflow and outflow are assumed to take place in the first compartment. The second compartment receives over-flow from the first, and this overflow is completely mixed. The inlet and outlets of the tanks are in the first compartment. As new water enters, it completely mixes with the first compartment and overflow is sent to the second compartment. When water leaves the first compartment, it receives an equivalent amount of water from the second compartment. Based on this information, the second compartment can have dead zones (Rossman, 2000).

- First In/First Out Plug Flow model (FIFO). This model assumes there is no mixing of water during the time it is in the tank. Water parcels are effectively stacked on one another, moving through the tank in a segregated fashion where the first parcel to enter is the first parcel to leave. This is most appropriate for baffled tanks that operate with simultaneous inflow and outflow (Rossman, 2000).
- Last In/First Out Plug Flow model (LIFO). This model assumes that no water mixing occurs in the tank. Water parcels still stack up one on top of another, and the last parcel to enter is the first to leave from the bottom of the tank. This is most appropriate for tall, narrow standpipes that have an inlet/outlet pipe at the bottom and low momentum inflow (Rossman, 2000).

4.5 Chemistry Modeling

The water models use the EPANET calculation methods for modeling chemical reactions. The EPANET method can model bulk and wall reactions, in regards to decay or growth. The bulk reactions used by these programs include: simple first-order decay, first-order saturation growth, two-component second order decay, Michealis-Menton Decay kinetics, or zero-order growth (Rossman, 2000).

There are two different types of reactions—bulk and wall, each discussed separately below. Figure 4-1 shows the differences in these reactions (Rossman, 2000).

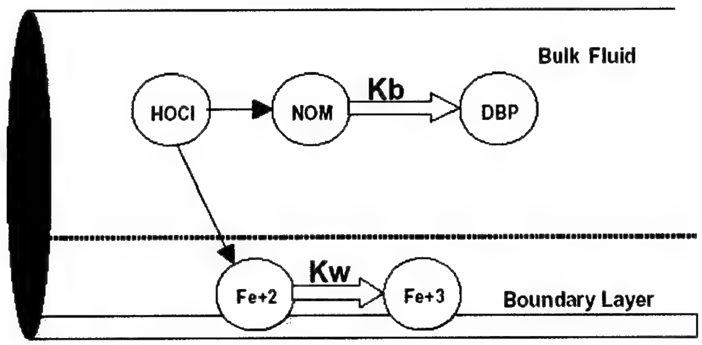


Figure 4-1 Pipe and wall reactions.

Each reaction should be considered very carefully. Some estimates are that up to 34% of the reactions occur in the wall phase with 17% occurring in the bulk phase. The remaining 49% occur in tanks (MWH Soft, Inc., 2002).

4.5.1 Bulk Flow Reactions

The programs model reactions in the bulk flow with n-th order kinetics. The instantaneous rate of reaction (R in mass/volume/time) is assumed to be concentration-dependent according to:

$$R = K_b C^n$$

Where:

- K_b = a bulk reaction rate coefficient. K_b has units of concentration raised to the (1-n) power divided by time. This is positive for growth reactions and negative for decay reactions.
- C = reactant concentration (mass/volume)
- n = reaction order.

There are other special case equations, described below. These equations are based on three parameters used to characterize bulk rates (K_b, C_L, and n). Table 4-2 summarizes the parameters and gives examples of a constituent that each would model.

Table 4-2 Summary of model parameters and examples.

Model	Parameters	Examples
First-Order Decay	$C_L = 0, K_b < 0, n = 1$	Chlorine
First-Order Saturation Growth	$C_L > 0, K_b > 0, n = 1$	Trihalomethanes
Zero-Order Kinetics	$C_L = 0, K_b <> 0, n = 0$	Water Age
No Reaction	$C_L = 0, K_b = 0$	Fluoride Tracer

The special case equations are discussed below. These equations are based on EPANET.

- <u>Simple First-Order Decay.</u> ($C_L = 0, K_b < 0, n = 1$)

$$R = K_b C$$

This can be used for the decay of many different substances, including chlorine.

- <u>First-Order Saturation Growth.</u> ($C_L > 0, K_b > 0, n = 1$)

$$R = K_b (C_L - C)$$

This can adequately model the growth of disinfection by-products where the ultimate formation is limited by the amount of reactive precursor there is in the water.

- <u>Two-Component, Second Order Decay.</u> ($C_L \neq 0, K_b < 0, n = 2$)

$$R = K_b C(C - C_L)$$

This equation assumes that substance A will react with B in some unknown ratio, which will produce product P. Based on the reaction, the rate that A

disappears is proportional to the product of A and B remaining. For this model, C_L can be either positive or negative and this value depends on whether either A or B is in excess, respectively. Some have had success in applying this model to chlorine decay data not conforming to simple first-order models (Clark, 1998).

- Michaelis-Menton Decay Kinetics. ($C_L > 0$, $K_b < 0$, $n < 0$)

$$R = \frac{K_b C}{C_L - C}$$

The programs will use the Michaelis-Menton Decay Kinetics when a negative reaction order *n* is specified, shown above for a decay reaction, but this is only a special case. The above is for decay reactions, but for growth the denominator becomes $C_L + C$. This equation is used frequently to describe enzyme-catalyzed reactions and microbial growth. Mathematically, it produces first order behavior at low concentrations and zero-order behavior at higher concentrations. For decay reactions, C_L must be set at a higher value than the initial concentration present (Rossman, 2000).

This equation was applied by Koechling to model chlorine decay in a number of different waters. It was found that K_b and C_L could be related to the organic content of the water and that its ultraviolet absorbance is as follows.

$$K_b = -0.32 UVA^{1.365} \frac{(100UVA)}{DOC}$$

$$C_L = 4.98UVA - 1.91DOC$$

where:

- UVA = ultraviolet absorbance at 254 nm (1/cm)
- DOC = dissolved organic carbon concentration (mg/L).
- Note that these expressions apply only for values of K_b and C_L used with Michaelis-Menton kinetics.

- Zero-order Growth. ($C_L = 0$, $K_b = 1$, $n = 0$)

$$R = 1.0$$

This is a special case that can be used to model the water age. For each unit of time, the concentration, or age, increases by one unit. There is a relationship between the bulk rate constant at one temperature (T1) related to another temperature (T2). This is often expressed using the van't Hoff – Arrehnius equation of the form:

$$K_{b2} = K_{b1}\theta^{T2-T1}$$

where: θ is a constant.

Use of the equations discussed above is predicated on some knowledge of the reaction coefficients. If the reaction coefficients are unknown, they will need to be measured in the lab or estimated with empirical relationships.

4.5.2 Wall Reactions

Substantial water quality changes can occur at or near the pipe wall interface. Wall reactions can be complicated, as it depends on temperature as well as pipe material and age. As metal pipes age, their roughness tends to increase with encrustation and tuberculation of corrosion products on accumulating on the pipe

walls. This in turn produces a lower Hazen-Williams C-factor or a higher Darcy-Weisbach roughness coefficient that results in greater frictional head loss through the pipe. Dissolved substances are transported to the pipe wall and react with materials such as the biofilm or corrosion products (e.g. iron oxides) on or near the wall. Several variables will influence this reaction. One of these is the area available for the reaction, which is simply the surface area per unit volume. Another variable is the rate of mass transfer between the fluid and the wall. The factor is represented by a mass transfer coefficient. The value of this mass transfer coefficient depends on the reactive substance's molecular diffusivity as well as the Reynolds number of the flow. The wall reaction rate can be considered to be dependent on the concentration in the bulk flow by using an expression of the form:

$$R = (A/V)K_w C^n$$

where:

- K_w = a wall reaction rate coefficient
- (A/V) = the surface area per unit volume within a pipe (equal to 4 divided by the pipe diameter).

The programs limit the choice of wall reaction order to either 0 or 1, so the units of K_w are either mass/area/time or length/time, respectively. The K_w value must be supplied by the modeler. The first-order K_w values can have a wide range, anywhere form 0 to 5 ft/day. The value should be adjusted to account for any mass transfer limitations in the moving reactants and products occurring between the wall and bulk flow. The programs do this automatically based on the substance's given molecular diffusivity and on the Reynolds number of the flow.

The programs can make the pipe K_w a function of the roughness coefficient. Note that WaterCAD does not have these calculations listed in the manual. The equations are listed below:

Headloss Formula	Wall Reaction Formula
Hazen-Williams	$K_W = F / C$
Darcy-Weisbach	$K_W = -F / \log (e/d)$
Chezy-Manning	$K_W = F\ n$

Where C = Hazen-Williams C-factor, e = Darcy-Weisbach roughness, d = pipe diameter, n = Manning roughness coefficient, and F = wall reaction - pipe roughness coefficient. The value for F must be developed from site-specific field measurements. It will have a different meaning depending on which head loss equation is chosen. This method requires only F to allow wall reaction coefficients to vary within the network.

Pipe wall reactions can also be expressed by using the following set of equations.

- First order rate.

$$r = \frac{2k_w k_f C}{R(k_w + k_f)}$$

where:
- k_w = wall reaction rate constant (length/time),
- k_f= mass transfer coefficient (length/time),
- R = pipe radius.

This would be representative in situations where chlorine is the limiting reactant. This might occur with reactions that involve complex organic compounds,

or those found in exocellular enzymes and metabolic products produced by biofilm on the pipe wall (MWH Soft, Inc., 2004).

- Zero order kinetic reaction.

For this equation, the rate cannot exceed the mass transfer rate, thus the equation becomes:

$$r = MIN(k_w, k_f C)(2/R)$$

where *kw* now has units of mass/area/time.

The mass transfer rates are normally expressed by the Sherwood number, which is a dimensionless number (*Sh*):

$$k_f = Sh\frac{D}{d}$$

where:

- D = the molecular diffusivity of the species being transported (length2/time)
- d = pipe diameter.

When the flow is fully developed laminar, the average Sherwood number through the pipe is expressed by the following:

$$Sh = 3.65 + \frac{0.0668(d/L)\mathrm{Re}\,Sc}{1 + 0.04[(d/L)\mathrm{Re}\,Sc]^{2/3}}$$

where:

- *Re* = Reynolds number
- *Sc* = Schmidt number (kinematic viscosity of water divided by the diffusivity of the chemical)

When the flow is turbulent, the following empirical correlation is used (Notter and Sleicher, 1971):

$$Sh = 0.0149\,\mathrm{Re}^{0.88}\,Sc^{1/3}$$

where all the values are the same as for the above equations.

MWH states that the zero-order model would be representative when chlorine immediately oxidizes some reductant (i.e., a ferrous compound) and the rate is then dependent on how quickly the reductant is made by the pipe. Based on this, this mechanism would apply mostly to corrosion-induced reactions (MWH Soft, Inc., 2004).

4.5.3 Estimating Reaction Coefficients

Unlike bulk reaction rates, wall reaction rates cannot be directly measured—they must be back-fitted against calibration data collected from field studies. This involves trial and error to determine the coefficient values that will replicate the same results that match the field data best. The type of pipe will have a large impact on this coefficient. There is not any expected wall demands for disinfectants for plastic and relatively new lined iron pipes (Rossman, 2000).

4.6 Uses of Models

There are several distinct uses for models in security applications. To be useful, the model must be calibrated for a wide range of alternative scenarios and be ready to apply rapidly in the EPS mode. The model must be set-up in an automated mode so that operation is represented by a series of logical controls established for the current operating procedures. This type of evaluation is possible, including the required data, but there have been only limited demonstrations of this type of operation have been accomplished so far. The obvious key to this is that the model

must be ready immediately because there would not be time to establish the model in an emergency. Security applications of distribution system hydraulic models include:

1. Detector placement. Models can be used to help determine the optimum placement of monitors. There are different approaches for determining where models should be located with the distribution system. Modeling is another technique to aid in this important task. Modeling can be used to determine the placement of a detector or can validate the placement of monitors already in the system.
2. Pre-event response scenarios. Extensive modeling could be conducted before an event occurs to facilitate response planning. Various scenarios can be input into a model and then run to determine the extent of the contamination and to develop and test response plans that will minimize any impacts. There are many variables that could impact this use, but using professional judgment for these variables will be an important factor to obtain the best type of responses. The response plan will be analyzed much quicker in the model.
3. Design/upgrade of water systems. Once the model is run and the possible contamination areas are highlighted, the next step will be to identify the weak points in the water system. There are two aspects to this use. First, flow patterns through neighborhoods can be seen in the model. System design modifications may be able to minimize these flow patterns, thus preventing flow from re-entering the major distribution lines and spreading to other areas. Second, optimal system design will include methods to isolate and flush the contaminants. After a response, the optimal solution will be to isolate the

contaminant and then conduct a proper flush, all the time ensuring the contaminant water is handled properly. No water system will be perfect in regards to isolating and flushing the contaminant without further impact to additional users; however, evaluation of the system through this method will allow utilities to pinpoint areas that need improvement.

4. Identifying location of contamination. During an actual contamination event, a model could be used to determine the location of the contaminant. When there has been a confirmed response, the model could be run with the data available to determine the input location of the contaminant. If the model is operated properly, this could be done relatively easily with a minimal amount of operating information.

5. Confirmation of positive event. One positive alarm from a monitoring may not necessarily indicate contamination. There could be numerous causes that would result in a false positive and therefore a reasonable approach for confirming a positive alarm must be developed. It would be unreasonable for a utility to immediately react as though the system was being sabotaged on only one reading; however, due diligence must be practiced to ensure a proper response is initiated to limit the number of casualties. Once a positive is detected, there would be a mobilization to verify the field monitors with other monitors. At the same time, another verification could be done with the model. This would be done through predicting where the contamination, if truly in the system, would travel to next and the appropriate reading that would be expected at that point. Once the water reaches that point and the

monitor responds in the model-predicted manner, the second response has been found. Depending on how the utility decides to respond (i.e., whether two or three positives are required prior to initiating a response), the response can be initiated. Note: in this scenario, the reaction equations will become important. If the constituent is assumed not to decay, then there may be a substantial overestimation of the level of constituent. This may lead to the conclusions that there was not a contamination event even though there was one.

CHAPTER 5. MATERIALS AND METHODS: *CRYPTOSPORIDIUM PARVUM* INSTRUMENT RESPONSE ANALYSIS AND MODEL APPLICATION

The objective of this analysis was to determine the level of *Cryptosporidium parvum* oocysts that could be detected using normally measured water quality parameters (total organic carbon, turbidity, laser turbidity, chlorine residual, pH, and conductivity). Once the level of detection was determined, the next objective was to determine if the monitors in the system could detect the oocysts. This would be completed through a water distribution modeling program. The detection level would be statistically based on the level of oocysts that would cause one of these parameters to exceed the 3-sigma value of the baseline water. The 3-sigma level was calculated from a baseline obtained just prior to the analysis of the oocysts.

This analysis involved three distinct steps. First, the oocysts were analyzed using beaker tests to determine the detectable levels. Second, the oocysts were analyzed using a constructed distribution system. Third, modeling was conducted to determine how the oocysts would act within a real distribution system.

5.1 *Cryptosporidium parvum* Oocysts

The *Cryptosporidium parvum* oocysts used were an Iowa bovine isolate from experimentally infected calves ordered from Waterborne, Inc., New Orleans, LA. There were several different options for ordering:

- Viable. Viable oocysts were shipped in phosphate buffered solution with pen strep and fungicide antibiotics. Waterborne, Inc., guaranteed these oocysts for one month from the date of shipment.
- Non-viable. These oocysts came in 5% formalin solution and were guaranteed for 6 months from the date of shipment.
- Freeze-killed. These were in suspension, in one of two solutions. They could be shipped in phosphate buffered solution (with or without antibiotics) or in de-ionized water (with or without antibiotics). Freeze-killed oocysts would have a certain amount of degradation, but that this amount could not be guaranteed.

Any volume of oocysts could be ordered. The company stated the oocysts would remain in that biological state; however, after the first month, only approximately 89 to 98% of the oocysts would be viable and intact.

The oocysts ordered were freeze-killed in de-ionized water without antibiotics. This research focused on the chemical changes the oocysts would cause, so they did not have to be viable. The parameter that would most likely be impacted by viable oocysts would be chlorine residual. Because the oocysts are only very minimally affected by chlorine, it was not anticipated that the freeze-killed oocysts would impact this variable.

The oocysts, as ordered, were P102 *C. parvum* oocysts, Iowa isolate, calf source, lot # 03-16, 1 x 10^6 in d H_20, 4 mL. The oocysts were freeze-killed.

5.2 Beaker Tests

Beaker tests were conducted first to attempt to determine the concentration of oocysts that would be detected. A specified concentration was made. Each of the

following parameters was measured for the tap water first, and then the sample containing oocysts. These were done to obtain the change in each parameter. Normal bench top equipment was used, including:

- Chlorine: HACH DR/3000 Spectrophotometer
- Turbidity: HACH 2100N Turbidimeter
- Conductivity: Oakton Instruments ECTestr
- pH: Fisher Scientific AR25 Dual Channel pH/Ion meter
- TOC: HACH astroTOC 1950 Plus

Dilutions of the oocysts were conducted to obtain the desired concentration. These dilutions were done based on the following equation.

$$C_1 = \frac{C_S * V_S}{V_1}$$

5.3 Distribution System Tests

The next step was to measure the contaminants in the laboratory pilot-scale distribution system. This system was constructed to model the water behavior in an actual distribution system as well as have locations to place the monitors. A re-circulation pump was used in the system to ensure the contaminants reached detectors. The pump used was an Easy-Load MasterFlex model 177601-10, manufactured by Cole-Palmer.

The same water quality parameters were measured, but laser turbidity was added to provide additional sensitivity. The on-line equipment that was used included:.

- Chlorine: HACH CL17 Chlorine Analyzer

- Turbidity: HACH 1720D Low Range Process Turbidimeter
- Laser Turbidity: HACH FilterTrak 660 ™ Laser Nephelometer
- Conductivity: GLI International Model C53 Conductivity Analyzer
- pH: GLI International Model P53 pH/ORP Analyzer
- TOC: HACH astroTOC 1950 Plus

This equipment is explained further in Appendix 1. Readings were taken every 30 seconds and recorded on a computer.

There were two pieces of information required for each water quality parameter—background and changes when the oocysts were added. To obtain a reliable background, water was run through the system overnight prior to the analyses. This allowed fresh tap water to run through the system for at least 12 hours and simulate real-world conditions more closely. The monitors and the re-circulation pump were turned on the day of each experiment. These were allowed to run for 100 minutes before the oocysts were added in order for a baseline to be established.

The oocysts were diluted in a one-liter beaker to the specified concentration. The oocysts were pumped into the distribution system using a MasterFlex Console Drive pump, manufactured by Cole-Palmer. Readings were taken every 30 seconds and recorded in the computer until the monitors returned to the background levels. The contaminant concentrations measured were 100,000, 200,000, 400,000, and 600,000, each in a volume of 0.5L. The volume used throughout these experiments was 0.5L because this was the assumed amount of water that a normal person would drink in one sitting.

5.4 Turbidity Measurements

The focus of the measurements was on turbidity because it has been a useful parameter for measuring *Cryptosporidium parvum* in drinking water. From the literature review, there were several outbreaks involving this pathogen that the only increased measurement was in turbidity. This was the case in the Milwaukee outbreak as well as the Bradford, England outbreak. Most of the turbidity readings during these outbreaks did not exceed the prescribed limits. Closer statistical analysis of the turbidity readings would hopefully show that turbidity would measure these oocysts at appropriate levels.

There are limits to what turbidity can detect. For instance, as the turbidity goes below 1.0 NTU, bubbles and particulate contamination can result in false-positives. Pure water has a turbidity of about 0.012 NTU. A single piece of dust or another particle can cause a spike of 0.030 NTU or more, and can result in errors exceeding 10 percent. Stray light can also be a significant source of errors in low levels. This occurs when light reaches the optical system but it is not from the sample. The stray light will increase in time as the dust contamination increases, thus scattering light. Stray light cannot be zeroed from the sample (Sadar, 1998). Despite these problems, turbidity was expected to be the most useful measurement. Additionally, it was expected that greater detection could be completed through the use of the laser turbidimeter because it can measure particles down to 2.0 microns (HACH, 2003).

5.5 Modeling

After the detection limits of the *Cryptosporidium parvum* were established, the data would be modeled using H2OMap™ software using the guidance established. The goal of the model was to determine if the intentional introduction of *Cryptosporidium parvum* oocysts could be detected and what the impact area would be from such a contamination.

The input of the model was determined by the amount of oocysts that would be available to the saboteur. The literature showed that it would be feasible for a saboteur to produce up to 0.4 kg of oocysts, difficult to make 4 kg, and very difficult to make 40 kg (Confidential Report #1). Based on this, it was assumed that 0.4 kg would be available for introduction into the water system.

The scenarios for a saboteur to impact a water security system are nearly endless. The objective of this modeling was to determine if this contamination could be done in such a way that it could be detected based on the detection limits as determined by the research. There were three different options that were considered to introduce the contaminant into the system: first, a high-volume backflow using a 35-gpm pump at 155 psi to introduce a dilute contaminant; second, a low-volume backflow, which would use a pump from 0.001 to 0.4 gpm and introduce a concentrated contaminant; and third, a backflow through a fire hydrant. This last scenario would include the use of a tank truck pumping at 750 gpm a volume of over 2,500 gallons, which would include a very dilute contaminant. Of these scenarios, the first two were chosen, that is high and low-volume backflow. Because of the nature of the oocysts, it would not be necessary to use a backflow through a fire

hydrant for several reasons. First, there would not be enough of the oocysts to necessitate this approach. Second, it would give attention to the sabotage efforts.

There were four scenarios analyzed. Scenario one was based on an attack within a developed area inside the system using a low flow pump. Scenario two was the same area but using a high flow pump. Scenarios three and four used the low flow and high flow pumps, respectively, but were located closer to a major water main.

Because of the nature of the oocysts and the low infective dose, a very low volume and flow rate would be required. Based on this, the low flow scenarios used a pump rated at 0.1 gpm. A volume of 5 gallons was assumed, which would equate 0.6684 ft^3 or 18.93 liters. Using the oocyst mass of 0.4 kg (400,000,000μg), the concentration of oocysts was 21,130,000 μg/L. The pump would then have an operation time of 50 minutes. The tank within the model was made to have the required volume for 0.6684 ft^3. This would have a diameter of 1 foot, and a length of 0.851 foot.

The high flow pumps used the same basic assumptions except the pump was rated at 10 gpm and the tank size was 50 gallons (6.684 ft^3 or 189.3 liters). The same mass of oocysts was assumed, which placed the concentration at 2,113,000 μg/L. The pump would then have an operation time of 5 minutes. The tank used had a diameter of 1 foot and a length of 8.51 feet to model the volume or 6.684 ft^3.

The output was based on the doses that could cause illness and the levels that were detected. The oral infective dose, in number of oocysts ingested, has been estimated to be 10 (Confidential Report #1), 30 (DuPont et al, 1995), 132 (Roefer et

al, 1996), to 239 (Hass et al, 1996). The concentrations that were detectable, as found through the distribution system tests, were also used.

The model included one pressure zone of a municipal distribution system covering approximately four square miles in a primarily low-density residential area. The model hydraulics were representative of the actual system but the model was not calibrated. The objective of the study was to analyze the spread of the contaminant, so the lack of calibration was not a problem. Demand and flow in the model represent average daily conditions (3.9 mgd), from which actual demand and flow may vary significantly according to season, day of the week, and other factors.

The water temperature was chosen to be 5 °C, which is typical of winter or early spring conditions in many water systems. A pH of 7.9 was selected, which is a typical target for many public drinking water systems to control corrosion. Alkalinity was set at 40 mg/L. This is a typical value for Colorado Front Range water.

Table 5-1 lists the simulation options used. Table 5-2 lists the time options used.

Table 5-1 Simulation options used in the model.

Headloss Equation	Hazen-Williams
Trials	40
Accuracy	0.001
Specific Gravity	1
Water Quality Tolerance	0.01
Viscosity	1.1e-005
Diffusivity	1.3e-008

Table 5-2 Simulation times used in the model.

Duration	24	Hours
Hydraulic Timestep	2	Minutes
Pattern Timestep	1	Hours
Quality Timestep	2	Minutes
Report Timestep	2	Minutes
Rule Timestep	2	Minutes
Pattern Start	0	Hours
Report Start	0	Hours
Start Clocktime:	00:00:00	(Midnight)

Small time steps were used to ensure accurate modeling. The contaminant injection began at midnight, which is the beginning of the lowest period of demand during the diurnal cycle.

CHAPTER 6. RESULTS AND DISCUSSION: GUIDANCE FOR MODEL USE

There are many reasons why models of flow, chemistry, and other key parameters are gaining importance in the water field. E. Timothy Oppelt, the Director of the National Risk Management Research Laboratory stated, “water utilities are feeling a growing need to understand better the movement and transformations undergone by treated water introduced into their distribution systems” (Rossman, 2000). Real time monitoring has become crucial. William Muszynski, EPA Region 2 Deputy Regional Administrator, stated the importance of such monitoring: “Whether a contaminant enters a water supply system by terrorist action or by accident, it is vital that we have the information to respond quickly. That’s why real-time monitoring offers such great promise” (Water Tech Online, 2004). Once this data is obtained, it can be analyzed through a model that will reveal a great deal of additional information, including the areas of contamination. Modeling can also help in determining if the sampling is a false positive.

New technology is making real-time monitoring possible. The EPA is now evaluating technologies that will alert water-system operators to a range of possible threats to human health including deliberate dumping of contaminants, sewage treatment plant failures, chemical spills, harmful algae blooms, and pollutants from stormwater runoff. It is interesting to note that in the past, major events have been relatively rare,

and because of this, there have been suggestions to curtail these early warning systems (Grayman and Males, 2002). However, there are new movements to increase the monitoring. For instance, the EPA recently allocated $500K to create a pilot project to provide system operators with real-time information about safety and quality of their water supplies. The technology exists, but it needs to be tested together in a real-world setting (Water Tech Online, 2004).

Modeling can also assist with determining the actual sampling sites. In order to select sample stations in a rational manner, understanding of flows in a system is absolutely necessary. Lee and Deininger state that no matter how complex the system, there are specific pathways for water to get to particular points (Lee and Deininger, 1992). In the past, much of the concern was on the water as it left the plant, even though the Safe Drinking Water Act of 1974 clearly specifies that the standards should be met at the tap (Clark, Grayman, and Males, 1988). The need for and development of water quality modeling was a result of the 1986 Safe Drinking Water Act Amendments that established standards at the point of consumption. This legislation forced utilities to consider drinking water quality in the distribution system and changes in quality that might occur following treatment (Clark, Rossman, and Wymer, 1995). Two specific regulations have shifted the focus to attainment of standards at the tap—the Surface Water Treatment Rule and the Total Coliform Rule. The Surface Water Treatment Rule requires the utility to maintain a detectable disinfectant residual at representative locations in the system to provide protection against pathogens. The Total Coliform Rule regulates coliform bacteria that are used as surrogates to indicate whether or not breakdown of primary disinfection is occurring (Clark, Rossman, and Wymer, 1995).

Additionally, under the SDWAA, the EPA is required to regulate levels of pathogenic microbiologicals in water—specifically *Giardia lamblia*, enteric viruses, and *Legionella* (Boulos et al, 1994). Modeling is one method to assist evaluating the water at the tap.

The final major reason for the use of modeling is to provide information regarding security of the system for intentional or accidental contamination. Information regarding the system will be crucial during an attack, especially for smaller communities, because even though the probability of a terrorist attack is a low, experts agree that it is not a matter of if, but when (Waeckerle, 2000). The same experts state that local communities must be ready to be self-sufficient for at least 24 hours because state and federal resources may not be available during that period (Waeckerle, 2000). Any information that will assist during this time will be extremely valuable.

Allman (2003) conducted modeling work to determine how the distribution system would respond to such an attack. He found that the flow direction in the system must be known, which illustrates the significance of the hydraulic information that would be needed for a sophisticated and highly effective attack. He also found that the flow pattern determined the contaminant spread. The patterns were surprisingly conducive to transporting contaminants from one neighborhood to another through most of the system.

Haestad Press gives the following example of a scenario in which the use of a model would be valuable. A call comes in from the police with information concerning a possible water contamination. The location, chemical, time, and duration are known. The first action is to notify the public. The second action is to determine how to flush the contaminant, i.e., which hydrants to open and for how long. Flushing can drastically change the way water moves throughout the system. Trial-and-error for the flushing

program would be long and risky. The best and easiest method is to use a model to analyze the flushing. Obviously a properly calibrated model would be required for such analysis and that model must be ready for immediate use (Haestad Press, 2003). These examples represent a few scenarios where flow models can be a powerful tool in water security analysis, both before an attack and the response afterwards.

In a real world scenario, much of the above information would not be available. If monitors are in the system, there may only be a positive response at one of the detectors. Therefore, a lot of information will be lacking. The use of models will help in the preparation for an incident, including proper instrument siting, confirmation of positive results, and then formulation and evaluation of responses. After an attack has been conducted, it is too late to develop a model to help in response. Therefore, it is crucial that the model be developed prior to a contamination event.

The guidance presented in this paper is broken into four distinct categories: general model development, security applications pre-scenario analysis, security applications post-scenario analysis, and detector placement. Each of these are presented and discussed below.

6.1 General Model Development

The security-specific guidance in this section is largely based on the assumption that the system model has already been completed and just needs applied in a water security manner. The time to get a model running is largely dependent on the condition and status of the existing model, but even if the model is in good operating condition, there can still be a major time investment. Some estimates are that if the model and GIS data is in good status, it can be operational in a short time frame of three to six months,

but this could be longer if the model is not fully developed (Bahadur, Samuels, and Pickus, 2003). The guidance discussed in this section is directed at developing a hydraulic model in preparation for security applications. A flow chart outlining the guidance for general model development is shown in Figure 6-1.

Determine Model and Model Size

One of the first steps is to choose the actual model and the size, both of which are important decisions. Each model has it strengths and weaknesses and these must be considered prior to model selection. Once that decision is made, the next decision is the size of model required. The size of model can greatly affect the price, so the size required is one that must be carefully determined to ensure the proper capabilities are achieved while minimizing the price.

Create Model

The next step, if not already completed, is data entry, or creating the basic model of the hydraulic system. The actual model creation is beyond the scope of this paper. This step will include data entry of the initial system parameters.

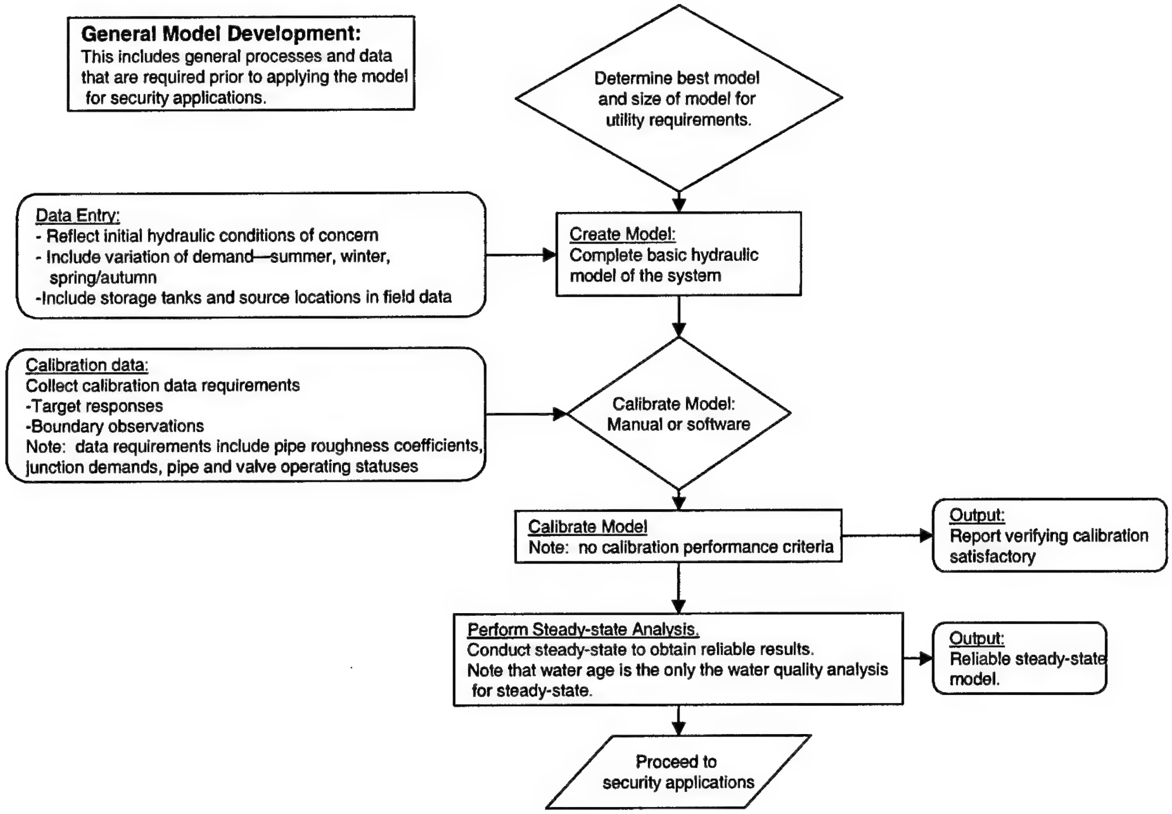


Figure 6-1 Flow chart for general model development.

Data Entry

There is a large amount of data that must be entered into the model. The model must reflect the initial hydraulic conditions of concern. It is impossible to model all conditions, but carefully selecting appropriate conditions will provide insight into most of the possible situations as opposed to just a few extreme days. The model must include a variety of demands, and not just the worst case such as a summer day. The model should include typical summer, winter, and spring/autumn days. When collecting the initial field data, it is recommended that storage tanks and source locations be included in the measurements (Rossman, 2000).

Calibrate Model

Calibration is the process of adjusting the model so that the predicted flows and pressures match actual observed field data to an acceptable level. This must be done to ensure the model is being used correctly and simulating the flow patterns properly, or to ensure it predicts the system properly (Haestad Methods, 2002). Calibration involves adjusting model characteristics and parameters so that the output matches the field data to an acceptable level (WaterCAD, 2004). In short, calibration makes the model credible. Without that credibility, the most complex and theoretically sound model that could be developed would not be effective in helping plan a sound system. A well calibrated model will not only result in more accurate water quality simulations but will also greatly assist in locating optimal sampling and satellite treatment locations and in making sound and cost-effective water quality management decisions (MWH Soft, Inc., 2004). Overall, calibration is essential to increase the knowledge and understanding of the system. There are no calibration performance criteria in the U.S. and there is no industry consensus about the acceptable threshold match although AWWA does have calibration guidelines (AWWA, 1999a).

There are many parameters that must be considered for calibration. The data required can be broken down into two main categories: target responses and corresponding boundary observations. The target responses are junction pressure and pipe discharges. The boundary observations are such items as tank levels, valve settings, pump statuses and speeds. Calibration typically consists of measuring the required parameters at different times of the day at different sites. These should correspond to different demand loadings and boundary conditions. Based on time and labor constraints,

only a small percentage of representative sample measurements can be gathered (Haestad Methods, 2002). Calibration can be done either manually or through relatively new calibration software.

Manual calibration.

Manual calibration is basically a trail-and-error process, which can become very tedious. It includes adjusting model inputs using only basic engineering judgment. This requires using all time-disjoint field data to ensure the model simulated the actual physical systems under all conditions (MWH Soft, Inc., 2004; Haestad Methods, 2002). The manual method requires the modeler to estimate the model parameters, run the model to obtain values, and then compare to the field data. Then the model values are changed. This is an iterative process that is repeated until the desired results are obtained. The process can be very time consuming, especially for larger systems (WaterCAD, 2004; MWH Soft, Inc., 2004).

Calibration software.

There are numerous models with water calibration software. These use genetic algorithms that allow the model to test millions of solutions and then it identifies the best solution. For instance, WaterCAD has a program called "Darwin Calibrator", which uses Fast Messy Genetic Algorithm (fmGA) to calibrate the model in steady state, multi-steady state, or EPS modes. This program allows manual changes if required (WaterCAD, 2004). MWH Soft Inc. offers H_2OMAP WQ Calibrator and H_2ONET Calibrator® extension for calibration, which use the Object-Oriented Messy Genetic Algorithms technology with advanced Elitist and Global Search Control strategies in a true high-performance GIS environment. The calibrator works to minimize the

difference between site-specific measurements (or residual concentration data) and the model concentration predictions (MWH Soft, Inc., 2004). EPANET has calibration reports, which tell how well the simulated results match the actual field measurements. These pages include:

- <u>Statistics Page:</u> Lists error statistics between those simulated and observed values at each location measured. The program will find values through interpolation if a measured value was completed at a time in-between the simulation's reporting time intervals.
- <u>Correlation Plot Page:</u> Shows a scatter plot consisting of the observed and simulated values for the measurements at each location in the network with each location assigned a different color in the plot.
- <u>Mean Comparisons Page:</u> Bar chart comparing the mean observed and mean simulated values for the calibration parameters for measurements at the each location they were taken.

The major disadvantage with these calibration software packages is the cost.

<u>Steady State vs. EPS</u>

There are certain water quality analyses that can be completed in the model. These will be discussed later, but those that are most useful can only be completed using EPS analysis. However, it is highly recommended that the model be examined under steady-state situations prior to using the EPS model. The will make it easier to complete the EPS analysis (Haested Press, 2003).

Once the model has been completed and run satisfactorily, the model is ready to be applied to a specific water security issue.

6.2 Security Applications—Pre-scenario Analysis

Once a satisfactory model has been developed and run, security specific applications can be developed. This section describes analyses that would be completed before a contamination event occurs. A flow chart for conducting the pre-scenario analysis is shown in Figure 6-2.

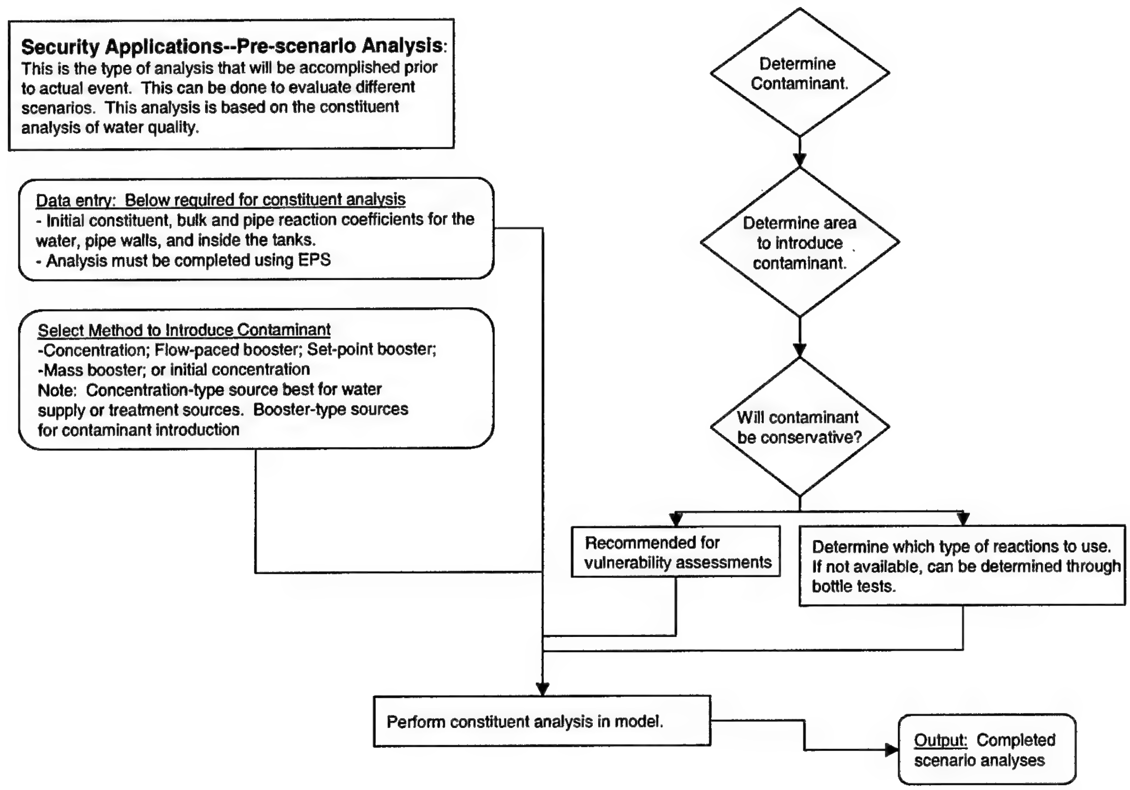


Figure 6-2 Flow chart for pre-scenario guidance.

There are three distinct types of water quality analyses that can be conducted (water age, trace analysis, and constituent analysis) and each requires different types of information. The constituent analysis would be the scenario most appropriate for water security because it allows direct input of a contaminant. Trace analysis can be useful if

the source of the contaminant is determined because this will show other areas impacted by the contaminant. Water age analysis can be useful to show how long the contaminant will be in the system, but is not the recommended analysis method. Water age can be performed using steady-state analysis, so it can be one of the first analyses performed. Each analysis requires different data input as explained below:

- Age. Requires pipe velocity and flow rate. No reaction rate coefficients are required.
- Trace. Requires pipe velocity and flow rate. No reaction rate coefficients are required. This analysis can only be performed using EPS.
- Constituent. Requires the greatest amount of information: initial constituent, bulk and pipe reaction coefficients for the water, and interaction between the water and pipe walls as well as tank reactions. If the contaminant is assumed to be conservative, these parameters will be zero. This analysis can only be completed using EPS (Haestad Methods, 2002).

Determine contaminant to use

The first step in water security modeling is to determine the contaminant to model. The actual selection goes beyond the scope of this paper, but will be briefly discussed. An ideal agent that would be used by a saboteur would be readily available and not easily detected by monitoring equipment. The physical appearance would have no odor, color, or taste. Dosage and health effects must also be considered. The agent must also be chemically and physically stable in the water as well as tolerant to chlorine (Haested Press, 2003).

There are many different methods available that have rated the effectiveness of contaminants. One such method is by Deininger and Meier (2000), who developed an equation to rank contaminants based on a factor of relative effectiveness. This is but one example of an equation to select a contaminant, but gives a general idea of selection criteria. R, is based on lethality and solubility, using the following equation:

R = solubility in water (in mg/L)/(1000 x lethal dose (in mg/human))

There are many different factors that can be used to select a contaminant. The contaminants range from those that cannot be easily detected and can be detected quite readily. It would probably be best to select an agent that is detectable for the first scenario because this would show where it could be detected. However, there are numerous contaminants that can be selected.

The contaminant is represented in the system by describing its transformation characteristics and how it was introduced into the system. The items that must be input include the time and the amount of contaminant that was placed into the system. Most models provide several alternatives to input this information.

Determine area to introduce contaminant

Once the contaminant is determined, the location in the system where it will be injected into the system must be determined. This could be any node in the system, so the possibilities are many. The actual location could be chosen from a vulnerability assessment conducted. It is recommended that many different sites be selected and evaluated. The sites should be from places throughout the system and also different types of nodes (i.e., large mains, small mains, inside buildings, etc.). One purpose of this analysis is to determine possible scenarios, so the more nodes chosen and evaluated the

better. Through choosing a wide range of nodes, certain sites that are more vulnerable may become obvious. Guidance on the selection of nodes can be evaluated through the case studies in this paper, that is, the nodes that others have chosen and are nodes that may present higher risks. Another consideration is nodes around high value targets, such as hospitals and schools. These areas may present ideal targets for saboteurs.

Determine Reaction Coefficients

The next step is to determine if the contaminant will be conservative or reactive. Reaction coefficients are normally treated as conservative or simple first-order kinetic (Boulos et al, 1994; Haestad Press, 2003), but are usually assumed to be conservative for security studies (Haestad Press, 2003). If there are not conservative, the reaction coefficients can be entered through various decay methods. Coefficients may be found for some contaminants in the literature.

Determining Reaction Coefficients if Unknown

If there is a need to determine the actual reaction coefficient for a specific chemical, it can be determined through bottle tests (Rossman, 2000). These cannot be used for wall reactions because they cannot be directly measured—they must be back-fitted against calibration data collected from field studies. This will involve trial and error but provide the best match to field data. The type of pipe has a large impact on this coefficient. Rossman does note, however, that there is not a large wall demand expected for plastic and relatively new lined iron pipes (Rossman, 2000).

The reaction coefficients depend on the type of pipe in the system. For example, unlined cast-iron pipes have higher chlorine consumption than polyvinyl chloride (PVC). Also, larger-diameter cast-iron pipes have lower consumption than smaller-diameter pipe

(Clark, Rossman, and Wymer, 1995). The water can have an impact also—water high in humic and organic material that is transported in the network can lead to pipes with a high disinfectant demand (Clark, Rossman, and Wymer, 1995). Biofilm on iron pipes are much more resistant to free chlorine than biofilms on galvanized, PVC, or copper pipe surfaces, which is probably because free chlorine reacts more ferrous iron to produce insoluble ferric hydroxide (Lu, Biswas, and Clark, 1995). These are just a few examples of the complexities that make estimating of pipe wall reactions difficult.

As shown, there are several different methods that the reactions coefficients can be estimated and represented in the model. The default for water security is conservative, that is, no decay. Most of the available literature also states that this is the preferred method. However, there can be potential problems with this in some aspects of modeling, specifically verifying a positive sample. If it is assumed that no decay occurs and if in fact there is decay, then the readings at down stream meters may be lower than anticipated. This may mean that the detectors will not read the expected values, and the conclusion could be made that there was not contamination in the system. This could be overcome by simple awareness, but this is still a consideration that the modeler must be aware.

Introduction of Contaminants

After the above decisions are made, the method for contaminant entry must be determined. There are several methods that contaminants can be entered into the system. These methods can be applied to anything from pipe breaks to intentional or accidental contamination (Haested Press, 2003; Rossman, 2000; MWH Soft, Inc., 2002). These methods are discussed below.

- Concentration: Fixes the concentration of any flow that enters the network at a node. Would be used for flow reservoir or a negative demand (a source) placed on junction.
- Flow-paced booster: Adds a fixed concentration to the flow. This results after mixing of all inflow to the node from other points throughout the network.
- Set-point booster: Fixes the concentration of any flow leaving the node. This can be used as long as the concentration resulting from all inflow to the node is below the set-point.
- Mass booster: Acts by adding a fixed mass flow to the flow entering the node from other points in the network.
- Initial concentration: Sets concentrations in tanks, changing over time due to the influences of either decay or dilution during fill cycle (Haested Press, 2003)

The EPANET and H2OMap™ manuals state that the concentration-type source is best used for nodes that represent source water supplies or treatment works, such as reservoirs or nodes assigned a negative demand. They also state that the booster-type source is best used to model direct tracer injection, introduction of additional disinfectant, or to model contaminant intrusion (Rossman, 2000; MWH Soft, Inc., 2002). Based on this, the booster-type source is recommended for contaminant introduction.

The contaminant information that must be input is discussed below. Note that these were taken from H2OMap™, but the other water quality simulations will require the same type of information (MWH Soft, Inc., 2002).

- Trace node. Used for trace analysis. The one node that acts as the origin for the tracing procedure must be specified.
- Chemical name and mass unit (usually mg/L). Self-explanatory.

- Global bulk. This value is the rate at which the chemical will grow or decay due to reactions in bulk flow of water
- Global wall. This is the rate at which the chemical will decay due to reactions with the pipe walls.
- Global pipe bulk reaction order. This value will be zero-order, first-order, second-order, etc.
- Global pipe wall reaction order. Unlike the term above, this will be either zero-order or first-order
- Global tank reaction order. This will be either zero or first-order.
- Limiting potential. This term is used to specify a limiting concentration that a chemical can either grow or decay
- Roughness correlation coefficient. This term relates to the wall reaction rate constant that is dependent upon headloss equation being used.

There are several other parameters that must be input for water quality models. These include relative diffusivity and quality tolerance.

- Relative diffusivity: This is the ratio of the molecular diffusivity of the modeled chemical to that value for chlorine at 20 deg C, which is 0.00112 sq ft/day. This value is used in the following manner: if the chemical diffuse twice as fast as chlorine, 2 will be used, if it is half as fast, then 0.5. This applies only for mass transfer for pipe wall reactions. If no effects, then it should be set to zero (Rossman, 2000).
- Quality tolerance. This parameter is the smallest change that will create a new water parcel in the pipe. A normal value would be 0.01 if the chemical is measured in

mg/L. The value of this parameter could be the detection limit of the procedure to measure the chemical as well as including a factor of safety also. If the value is too large, the accuracy of the simulation will suffer. If the value it too small, it will impact computational efficiency. Selection of this criteria may require trial and error (Rossman, 2000).

Simulation Duration

The simulation duration must be entered, which is usually some multiple of 24 hours because it is the most recognizable pattern for demand and operation. For emergencies, it may be better to model just a short time in the future in order to make predictions on immediate changes in tank level and system pressures. Other applications may require several days in order for certain parameters to stabilize. The hydraulic time step is normally assumed one-hour, unless other reasons dictate need for different time step (Haested Press, 2003).

The variables that must be entered are listed below, with typical values included:

- Total Duration: Total time of simulation in hours. 0 means single period (steady-state).
- Hydraulic Time Step: Time between re-computation of hydraulics. Default is usually 1 hour. Quality Time Step: Time between routing of water quality constituent. Default is usually 5 minutes.
- Pattern Time Step: Time used with all time patterns. Default is normally 1 hour.
- Pattern Start Time: Hours that all time patterns being. Value of 2 means that the simulation beings with the time patterns at their second hour. The default is 0.

- Reporting Time Step: Interval between times that results are reported. Default is 1 hour.
- Report Start Time: Time that computed results begin to be reported. Default is 0.
- Starting Time of Day: Clock time that simulation begins. Default is midnight.

Once these decisions are made and the data entered, the model can be run for numerous scenarios. This data can be changed relatively easily so that different nodes and chemicals can be evaluated. There will be a certain amount of engineering judgment that must be used to determine the locations for contaminant entry. Overall, the more scenarios that can be run, the better.

6.3 Security Applications—Post-scenario Analysis

This section will describe analyses that can be completed after an event has occurred. There could be various scenarios that could trigger this: a received threat, saboteur caught contaminating the system, or a positive response in the system from a monitor. There are two major goals with this analysis: verify a contamination event occurred and then determine and evaluate a course of action. A flow chart for conducting the post-scenario analysis is shown in Figure 6-3.

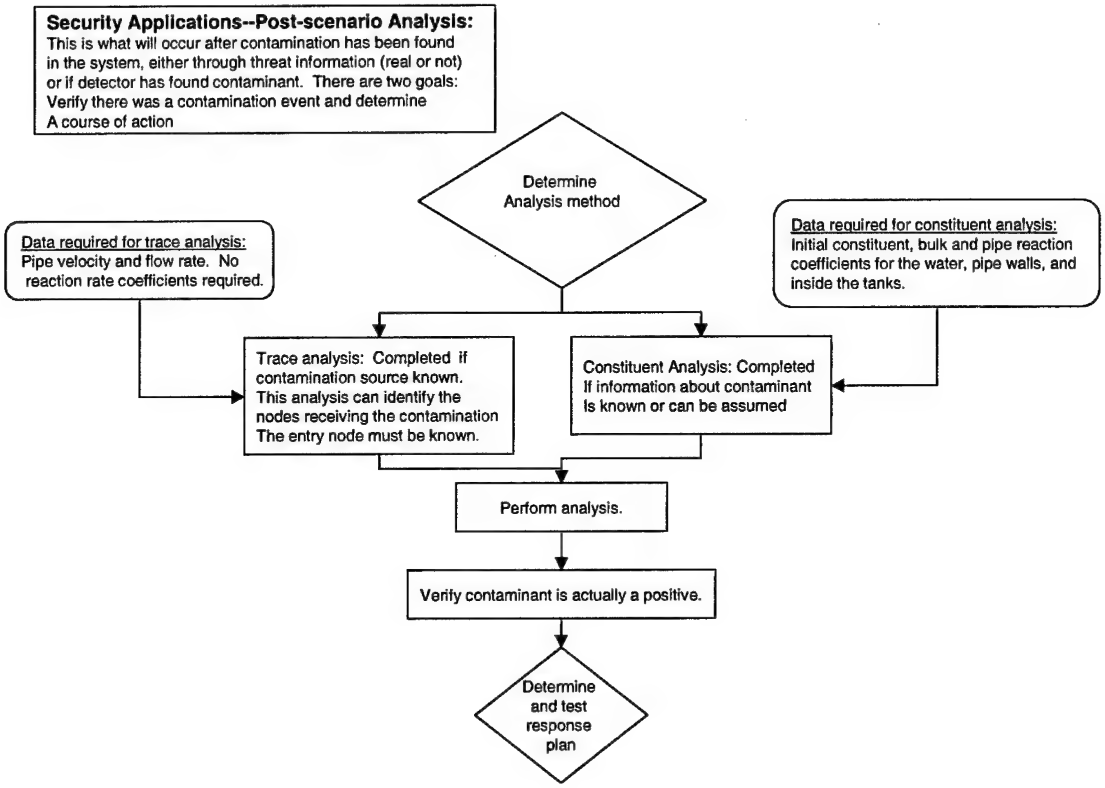


Figure 6-3 Guidance for post-scenario analysis.

Determine Analysis Method

The first step is to determine the analysis method. There are two methods that can be useful in this situation—trace and constituent analysis.

- Trace analysis: Trace analysis would be useful if the contamination source is known, i.e., the threat is known or the saboteur was caught. This analysis could then be used to determine where the water went throughout the system and determining the other nodes that are impacted. This method can also determine how much of the water at each node is impacted by the contaminant, e.g., the percent of that node that contains contaminant. The strength of this analysis is that it would be able to identify those users impacted. It may have limited use though because the actual node the

contaminant entered must be known, which likely will not be the case. This would require the same data entry as stated above.

- Constituent Analysis: This type of analysis would be completed if information about the contaminant is known or can be assumed. This would occur if a monitor detected the contaminant in the system. This would provide more useful information in this situation than the trace analysis, but it would also require a lot of information that must be assumed. This analysis will also provide information on those customers affected (through contour lines). Again, this would require the same data as stated above.

Once it is determined which analysis will be run, the analysis should be performed and as much information as to the contaminant travel must be obtained.

Verify Contaminant

There must be some type of method to verify that the contamination was actually an event and not a false positive. This is a very careful balancing act. If the event is a false positive and it is reacted to as a true event, a tremendous amount of resources can be wasted. However, if it is a true event, there could be many lives put at risk if it is not responded to quickly. Based on this, verification is a crucial step in this entire process.

Modeling can play an important role in verifying the contaminant. If there is a positive read at some point in the system, that data could be entered into the model from that point. The data, again, may be very limited, but if there is a positive in the system, then some basic information will be known. For instance, if there is a positive for conductivity, then some type of contaminant can be assumed and then modeled.

Once the known information is input into the model, predictions about the contaminant travel can be made through the contour lines. This will show the utility where the contaminant is heading and at what concentrations. This can and will show at what point the contamination will hit another monitor and at the expected concentration. Once the water does reach the monitor, verification is given if it is a positive at that monitor. The utility would not have to wait until the flow hits another monitor—the model can show where a verification sample can be taken and workers then sent there to collect samples.

Through these uses, the model can help in the verification. These are important steps that will help optimize uses of resources and maximize response.

Determine and Test Response Plan

Once it is determined that there was a positive in the system, a response plan can be developed. The first response would be to notify the affected consumers, which will be shown through the model. The nest step would then be to formulate a response, such as flushing and/or treatment strategy. The actual response design is beyond the scope of this paper, but once developed, it can be tested in the model. If it is satisfactory, then it can be applied. If it is not satisfactory, then another response plan must be developed and tested. This will likely be an iterative process to some extent, but time will of course be limited.

6.4 Detector Placement

The final use of models for security related applications is detector placement within the system. There are several major decision steps in this process as shown in Figure 6-4.

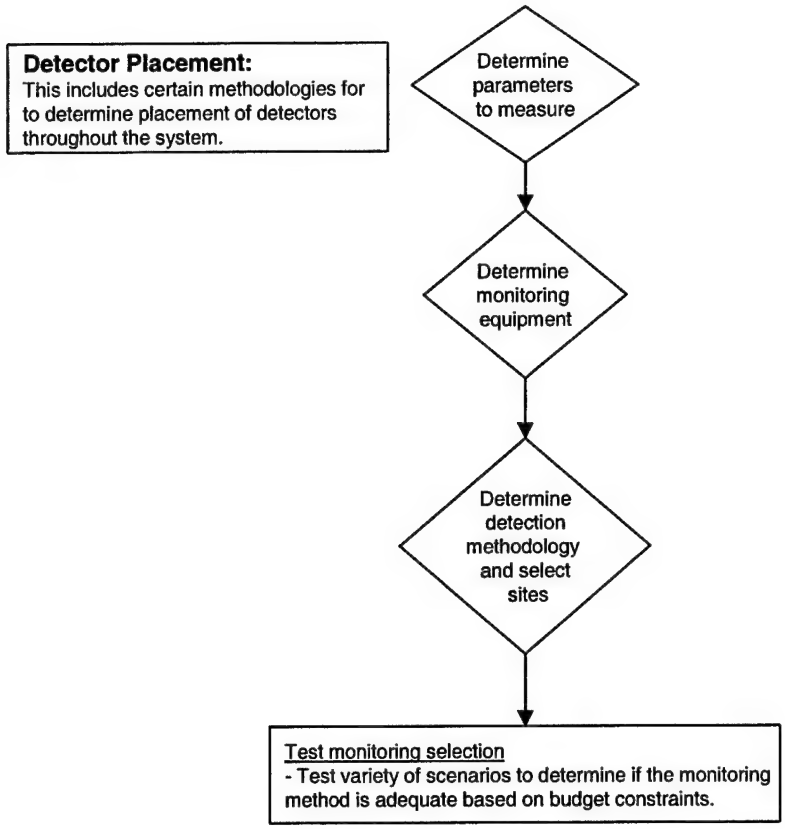


Figure 6-4 Guidance for detector placement.

Determine Parameters to Measure

The first decision point is the type of parameters to measure. This coincides closely to the monitoring equipment that will be chosen; however, this is a distinct decision. For instance, normally measured parameters can be chosen (turbidity, conductivity, chlorine, etc.) offer some easily obtainable values at relatively cheap prices. Obviously other parameters can be measured also, but will come at a much more expensive price as well as maintenance. These issues are discussed in other papers to a greater extent; however, the decision must be made as to what parameters should be measured.

Determine Monitoring Equipment

The next step is the actual monitoring equipment, which will be based on the parameters to measure. There is a wide range of online monitoring equipment available (AwwaRF, 2002), and each of these can be broken down into several distinct categories (Haested Press, 2003).

- Conventional sensors. Those monitors in this group are relatively inexpensive, widely available, and easily used. These do not provide a lot of information useful for identifying the presence of most contaminants. Those instruments in this category include DO, pH, conductivity, temperature, and turbidity.
- Advanced sensors. These monitors are more expensive, require greater expertise and maintenance, but are more effective at identifying the agent. This category includes gas chromatographs and spectrophotometers
- Bio-monitoring. This category has been in place for almost 20 years, but is still an emerging technology.

There are other emerging technologies that include electronic noses, DNA chips, flow cytometry, immuno-magnetic separation techniques, and online bacteria monitors. Other monitoring sensors are available, but go beyond the scope of this paper.

Even though there are a lot of new detectors available, they may not be the most cost effective methods. First, they can be very expensive and require a lot of maintenance. Second, because of the cost, there will be limited access. Third, high tech instruments will be able to detect only certain chemicals. For these reasons, a broad spectrum may be more beneficial. Normally used instruments will be cheaper, thus more can be purchased. They also may be able to pick up more chemicals through advanced

data analysis, which has been shown to be possible through theoretical calculation of chemicals at toxic concentrations (Allman, 2003). There are other examples of this, as shown by Kessler, et al, when they used turbidity and conductivity meters to detect contamination caused by wastewater or surface runoff intrusions (Kessler, Ostfeld, and Sinai, 1998).

Determine Detection Methodology and Selection of Sites

The next item to be considered is the actual sites to place the monitors. There are several methodologies presented in the literature for determining where to place monitors and some of these are discussed below. Models can play an important role in the site selection as well as evaluating the monitoring sites afterwards. Each water system has unique features; therefore, the monitoring should be based on each individual system (Bahadur et al, 2003)

Bahadur, et al, developed an approach to monitoring site selection based on three tasks.

- Task 1 – Determine appropriate location of monitoring points in the system. These were based on protection of critical populations such as hospitals, monitoring water quality at high vulnerability areas, and still enabling a proper response.
- Task 2 – Determine appropriate timing and frequency of monitoring. This was based on the intent to perform routine screening of system water quality and the intent to develop a suitable response to a suspected or known contamination incident in the network, which would be isolation or decontamination.
- Task 3 – Determine monitoring and water quality parameters to be measured. These should include determining parameters to measure, how to interpret the data, and then

how to identify the procedures, monitoring, and methods to determine water quality changes (Bahadur et al, 2003).

Using this approach, the authors found that optimal location of monitoring states is complex and dependent of many interlinked parameters (Bahadur et al, 2003).

Allman used a different method to place the detectors. Through his analysis, he found that there are common paths that the contaminants will travel. He found that the water moved in sheets through the neighborhood and not around them through the distribution lines. There were common paths for the transport of these contaminants, and these then became areas for detectors.

The ability of the contaminant to spread is based on pipe velocity, pipe flows, and pipe bifurcation, all of which are input into models. Areas with high flow rates posed a much higher risk to the overall system. Also areas with several branches occurring immediately upstream had a large impact on dispersal of contaminant. It was these flow patterns that determined the contaminant; therefore, knowledge of these flow patterns are crucial for determining the contaminant spread. The common paths were used to determine their suitability as detection sites. The criteria for detection site selection included the size of the upstream area that could be monitored at the location, the detectability of contamination occurring in this area, and the timeliness of detection. The results showed that certain areas were difficult to detect. The detectability was greatly impacted by mixing, which could reduce the concentration to below the detection limit. This means that locations where large quantities of water are mixed are not suitable for detectors. There were four locations selected to examine the performance of a theoretical system of detectors at these locations. The selection of those sites showed that

contamination in the lower parts of the system was significantly more difficult to detect because the contamination did not move and spread quickly based on the low flow rates and velocities. The same characteristics that make the chemicals difficult to detect (low flow rates and velocities), also present a low health risk. The greater the spread of the contaminant, the more likely it will hit a detector. Based on this, the methodology of detection site selection must be based on health risk.

Lee and Deininger developed another monitoring method. They stated that water quality parameters decrease with time and distance from the source. This led them to develop several conclusions in regards to detector placement—if water is good at a downstream node, then it must be good immediately upstream as well, thus the condition of water can be inferred based on other sampling. They do note that this logic is most suitable for gradual deterioration in water quality, and less appropriate for a quicker deterioration such as an external source. If this type of logic were applied, then the monitoring would only need to be accomplished at the furthermost point downstream in a long pipe. This is not appropriate for sabotage-type monitoring because it does not have good time-to-detection, which they claim is the most important variable and should be considered in the design process (Lee and Deininger, 1992).

Another paper presents other design methods for detecting contamination, which provides useful information even though it was based on accidental contamination. The methodology allows capturing accidental intrusion of contamination within given level of service and is aimed at identifying the best monitoring locations. The method was developed to find the optimal layout of detection system to capture any accidental

contaminant entry within a pre-specified level of service. The detection system was based on the following concepts (Kessler, Ostfeld, and Sinai, 1998):

1. The level of service of the detection system is measured by the consumed volume of contaminated water prior to detection (i.e., detection before certain volume of water is consumed)
2. Pollution due to external intrusion is propagated by immediate flow pattern and flow patterns that follow. Because the contaminant can enter at any location, the propagation is possible by infinite number of flow combinations.
3. Domain of detection for a particular node includes all nodes that are subject to contamination following an accidental pollution at that node.

The authors then established a methodology for establishment of a detection network, broken into five steps (Kessler, Ostfeld, and Sinai, 1998):

<u>Step 1:</u> Conduct a hydraulic stimulation covering average demand cycle, such as one day or week.

<u>Step 2:</u> Construct auxiliary network, which includes a set of nodes and directed arcs.

<u>Step 3:</u> Determine shortest paths of water and find the minimum travel time between the nodes.

<u>Step 4:</u> Develop a pollution matrix, which is made to represent the domains of detection and coverage of each node of the network

<u>Step 5:</u> Determine the minimum covering set, which includes minimum number of columns (or stations) that cover all the rows (possible sources of pollution). Following this, the initial cost is determined.

There are just a few examples of different methodologies that can be used for site selection. Each of these should be considered for the individual systems and then the actual sites determined based on the hydraulics of the system.

Test Monitoring Stations Selection.

After the selection sites are determined, they should be tested in the model with different scenarios. This will show the strengths and weaknesses of the selection sites and how they can be changed. This type of analysis would follow the same type of analysis presented above.

6.5 Case Studies

Models have been used for many different uses, but they have not been used tremendously for security-related issues. Understanding these uses and their application is important to optimizing model use as applied to security issues. These uses are explored further in the following case studies.

6.5.1 Case Study I.

Allman (2003) completed a study for modeling and detecting chemicals in a water distribution system. H2OMap™ was used to model one pressure zone of a water system in a primarily low-density residential area covering approximately 4 square miles with an average demand of 3.9 mgd. The model was not calibrated, but did represent normal hydraulics in the area. He used small steps—15 seconds for the high flow scenario (hydrant pumping) and one minute for the others. The pipe throughout the system was assumed to be PVC because it is non-reactive with most chemicals, thus was a conservative choice. Because of this choice, pipe wall reactions were not considered. Also, a worst-case temperature was chosen (5 °C), which is the typical temperature for

many systems in winter or early spring and would reduce the amount of chemical decay. Alkalinity and pH were chosen to be 40 mg/L and 7.9, respectively. These values are typical for the type of water system he modeled.

The chemicals modeled were parathion, sodium monofluoroacetate (Compound 1080), VX, and cyanide, and were chosen based on availability, lethality, potency, and persistence. Decay rates were determined as much as possible from the literature. Contaminant injection began at midnight. Both toxic and fatal doses for the contaminants were determined and converted to the applied concentration necessary to achieve this delivery assuming 0.5 L water consumption by a 60 kg person. These applied concentrations were adjusted for low solubility (parathion) and the taste and odor threshold (cyanide). The maximum amount of cyanide and 1080 assumed to be obtainable was 1000 pounds. Based on toxicity, VX only required 30 gallons.

There were three different methods for introducing the contamination into the water system. Table 6-1 lists the parameters for the contamination scenarios. Strategic locations within the system were chosen for contaminant injection. Figure 6-5 shows where these contaminants were injected into the distribution system. Using the same feed rate at each location was not practical based on the water flow in each area. Contours were completed to show the level of contamination throughout the system. Figure 6-6 shows these contours.

Table 6-1 Parameters for metered contamination scenario.

Contaminant	Toxic Goal	Target Concentration (mg/L)		Feed Conditions (g/L)	
Parathion	max solubility	24	At min hourly flow	1260	pure product
VX	$4\times LD_{50}$	4	At max hourly flow	1008	pure product
1080	LD_{50}	240	At max hourly flow	1000	dissolved
Cyanide	LDL_o	171	At max hourly flow	370	dissolved

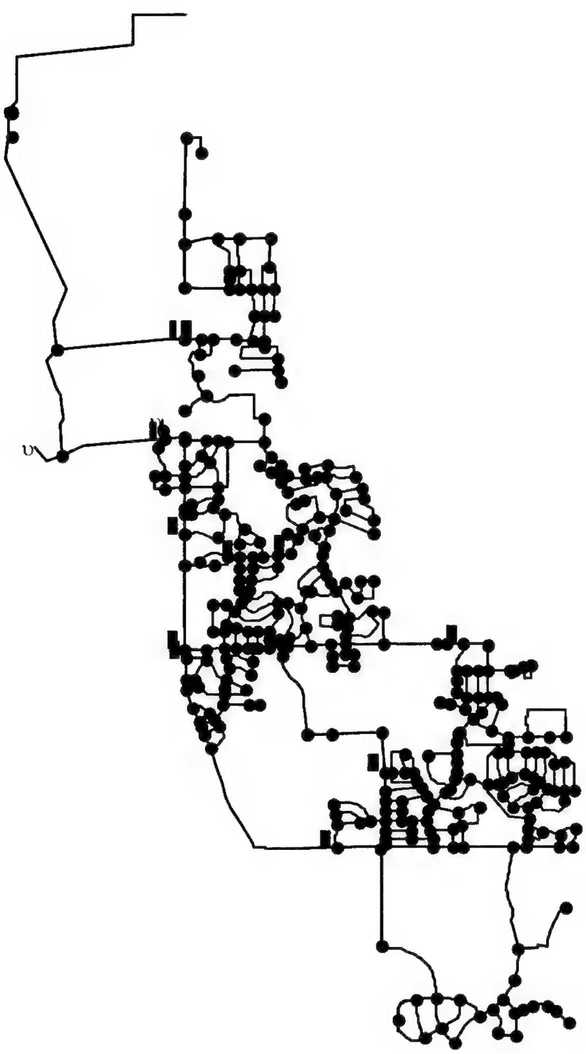
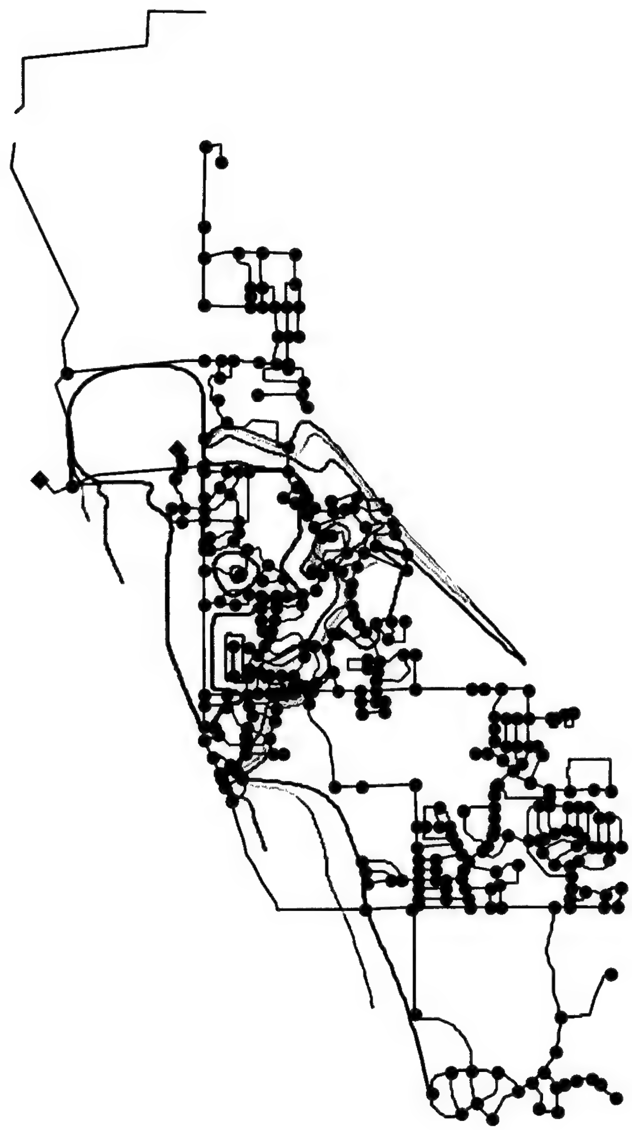


Figure 6-5 Points of injection for modeled contamination.



—	LD_{50}
—	LDL_o
—	Potentially Fatal
—	> Safe Dose

Figure 6-6 Spread of 1080 contamination from location 1 after 3 hours.

Based on this, the total quantity of contaminant injected at each location was determined by the flow rate. The areas with the highest flows thus had the largest impacts on the system. The spread was then modeled and recorded after 3, 6, 12 and 24 hours of injection. The contamination was quantified according to the proportion of the system demand affected. The three different scenarios were evaluated for the worst-case contaminant injection conditions described above.

The first scenario involved continuous covert backpressure feed into the system, using a standard ¾-inch diameter service connection with a small pump, operating at flows of 0.01 gpm or less. This delivered smaller quantities of a pure, highly concentrated contaminant just above system pressure. This method would give the saboteurs an advantage because of the delay caused by the time needed to displace the water in the service connection pipe. This could amount to hours before the contaminant reaches the distribution system, depending on the feed rate and length of the service connection. This could allow the perpetrators to flee before any ill effect occurs. This method was selected as the feed method of greatest concern.

The second scenario was similar to the first, except it used a larger pump, rated at 35 gpm at 155 psi, thus creating high flows of a dilute dissolved substance under high pressure. This high flow of a diluted contaminant would require capability for a large quantity of stored water because the backflow through the service connection will not allow for any water to be supplied to the building. This scenario would require mixing of the contaminant, which could be harmful to the saboteurs. The high pressure could also cause leaks in the building and detectable increases in pressures and flows within the

system. The additional water pumped into the system would increase pipe velocity and speed contaminant spread. If the additional volume causes the upstream flow to reverse, a second direction for contaminant spread within the system could be opened.

The third scenario included a tank truck with a built-in pump that would unload contaminated cargo through a backpressure into a fire hydrant in just a few minutes. The rates for this were at 750 gpm or greater. This has the same limitations as the high flow scenario as well as the volume that can be transported including the visibility and noise of the truck and tank. The primary problem with this scenario is the necessary speed of the attack. Because the contaminant is introduced into a flowing stream of water, the volume affected is the product of the flow rates and the length of injection. If the time is limited to several minutes, then even at high flows such as in large mains, the volume of water impacted is in the thousands of gallons. The impact of this is limited because only 1 to 2% of drinking water is actually consumed, thus dispersion of the slug of water is not considered significant. Mixing can also produce larger quantities of water more dilutely contaminated. If the model is highly looped, the multiple paths allow the slug to mix with unaffected water resulting in multiple slugs passing through many locations in the system, which can still produce potentially toxic water albeit diluted.

After evaluation of these scenarios, it was determined that the low-volume, pure product metering approach was the most dangerous, which was then selected for further study. This scenario was then applied to several different locations in the system to determine the impacts on the system as well as possible detection scenarios. For the study, it was assumed that the objective of the actions would be to obtain the maximum toxicity with minimum indication of contamination.

Contaminant Detection

An important aspect of the case study was contaminant detection. Detection of the parameters was based on a significant change in a standard drinking water quality parameter, defined as a variation greater than 3σ from the mean baseline value. These variations were established using five parameters measured with real-time instrumentation over a six-day period. The parameters were turbidity, chlorine, total organic carbon (TOC), pH, and conductivity. The primary detection for the organics was TOC. Detection limits for parathion, VX, and 1080 were calculated based on their carbon content. Cyanide is inorganic; however, bench tests showed that TOC could be used to detect it. pH also offered an effective detection method for cyanide due to the acid-base reactions that occur with this compound. Another detection method for cyanide was conductivity since the TDS concentrations would be elevated (Snoeyink and Jenkins, 1980). Based on these detection methods, all of the chemicals except VX can be detected at concentrations below those that would be necessary to cause a significant acute hazard to human health.

Placement of Detectors

The model was used to evaluate the placement of detectors throughout the system. The contour lines were used to show the expected transport of contamination. This information was then used to find common paths of contamination, which were then evaluated for detector sites. Several different criteria were used to site the detectors—size of the upstream area that could be monitored at the location, detectability of contamination occurring in this area, and the timeliness of detection. The amount that could be detected was greatly impacted by mixing, so there were locations where large

quantities of water are mixed and therefore not suitable for detectors. From these variables, four areas were selected for detectors. VX was chosen as the contaminant because it would be the hardest contaminant to detect. Table 6-2 shows the time at which contamination was detected at the detectors from the various points of origin. The first point of detection is in bold.

Table 6-2 Time of detection by origin of contamination and detector location.

Contaminant Origin	Detector Location			
	#1 J430	#2 J378	#3 J632	#4 J540
1	**2:50**	3:42	8:42	2:58
2	3:08	2:40	9:34	**1:54**
3	ND	ND	9:20	**1:28**
4	ND	ND	*	**1:14**
5	ND	ND	**	ND
6	2:22	**1:52**	9:30	***
7	**1:00**	3:16	7:26	ND
8	ND	ND	**3:42**	ND
9	ND	ND	**6:10**	ND
10	**4:46**	9:04	20:34	ND
11	ND	**2:00**	10:20	****

Time from injection to detection given as hours:minutes
ND = not detected
*Approximately 40% of the detection limit at 16:10
**Approximately one-half the detection limit at 10:20
***Approximately one-half the detection limit at 5:30
****Approximately one-half the detection limit at 5:00

It was found that the contaminant in the lower parts of the system was significantly more difficult to detect because it did not spread quickly because of the low flow rates and velocities. Based on the flows in these lower areas, there would be a lower threat in these areas. This showed that it was not possible to detect the contamination in all areas of the system. Based on this information, the detection should be risk based.

System Upgrades

The analysis showed that flow patterns and pipe bifurcation play important roles in contaminant propagation. Those areas in the middle of a neighborhood did not present

as large of a hazard as those directly upstream of the neighborhood while those areas with branches immediately downstream had a large impact. The analysis showed that water passed through neighborhoods in sheets, with downstream mains acting as major receiving lines. This means the contamination will pass from one neighborhood to another, eventually hitting another main, then transported further downstream. The contaminant will be diluted, but still make it downstream. The spread of contaminant in the smaller lines was virtually the same as the larger ones; however, the greatest danger is still on major supply lines. If decay is minimal, lethal concentrations can be reached far downstream, representing the greatest potential danger from contamination. The flow direction must be known if a sophisticated and highly effective attack is to be achieved, but the overall results show that that large-scale contamination of a drinking water system can be accomplished through backflow into major network water supply lines. In addition, points of attack outside the major supply lines can also produce large-scale contamination but at lesser concentrations.

Randomly selected points for contamination can impact large areas depending on pipe velocities, flow patterns, and other factors. In order to be successful, detailed system knowledge would be required. Gross contamination of the system would be easy, but also detectable. Mass casualties would be avoided, but there would be fear created.

Finally, the risk posed by a contaminant it is usually proportional to the ability to detect it because the risk is represented by the spread of a contaminant. The greater the spread, the more likely a contaminant will hit a detector. Mobile contamination that presents a large risk to a large part of the system can be detected and this must be the focus of a monitoring system. A loose grid detection system will only detect after a

significant portion of the system has been contaminated. Only a highly dense detector system will allow both detection and response in a timely manner to ensure control of the contamination. Based on this, it was concluded that detection must focus on the risk incurred by the incidence of contamination in certain locations and how far the contaminant will spread in significant concentrations.

Application and use of model

This case study demonstrates several important aspects of modeling. Through the use of the model, detector placement was evaluated. This was done using flow propagation information in the model. If another detection methodology is chosen and used, it can also be tested using modeling to determine its effectiveness. The scenario also showed how contamination location can be identified. This was done through the use of contour lines. The scenario also showed that flow patterns and pipe bifurcation play an important role in contamination. This information can then be used to upgrade the system as needed.

6.5.2 Case Study II.

A project was completed by Bahadur, et al (2003), using PipelineNet for a case study of the East Bay Municipal Utility District (EBMUD) in Oakland, California. The case study addressed the following issues: location of monitors in the system, timing and frequency of monitoring, and monitoring techniques and water quality parameters. The study evaluated 13% of the 122 pressure zones in that distribution system using a fully calibrated EPS model. The study area considered all pipes with diameter equal to or greater than two inches. The model run included 17,997 pipes (748 miles), 16 different pressure zones, and 16,878 junctions. The model was calibrated by adjusting model

parameters until acceptable values were obtained. This was accomplished by comparing the SCADA data to the simulated water tanks over a 24-hour period (Bahadur et al, 2003). There were three additional tools developed for PipelineNet used in this study:

- Consequence Assessment Tool. Provides quick identification and quantification of the areas at risk from contamination, including population, infrastructure, and resources. This tool calculates the population at risk, taps contaminated, total pipe (in miles) contaminated, number of hospitals and beds, and the number of schools and students within the area.
- Isolation Tool. Allows change in status of any pipe in the system, i.e., open or close each pipe, to control the flow of water.
- Spatial Database Display Tool. Used for determining the optimal placement of extraction and monitoring devices as well as predicting where the contaminant will move (Bahadur et al, 2003).

Detection

Sampling locations were chosen based on protection of critical populations and high vulnerability areas based on a proper response. The timing and frequency of sampling was based on performing routine screening while providing development of a suitable response to the incident. The last aspect included determination of parameters to track as well as interpretation of the data. One basic question that is hard to answer is how many samples should be analyzed. For contamination, sample numbers needs to be defined based on the flow of the contaminant in the system at different times, thus professional judgment must be used. The answer must be based on an objective approach

dependent on several factors including the desired statistical power and confidence level in the final decision as well as the variability of the environmental attribute of interest.

The case study developed a hierarchal selection process for monitoring locations, based on model inputs, outputs, and GIS layers. This included evaluating all elements of the water system initially, which was then reduced based on water utility priorities. These priorities included nodes physically accessible, high priority areas based on flow, velocity, pressure and water quality, and proximity to critical areas, such as schools and hospital. There was a three-step process used to rank the sites.

- Step 1: Prioritization of sources. Not all nodes in the system are available for sampling, so those inaccessible or unavailable were eliminated. These included nodes not physically inaccessible; junctions of two pipes with different diameters or materials; nodes of dead end pipes; nodes near crosses, tees, or other such items; nodes on transmission pipes, and nodes with backflow-preventers. These nodes were then considered not available for sampling.
- Step 2: Distribution System Response. The hydraulic and water quality results from the model are used to determine the distribution system response. The authors used the model to evaluate four sets of parameters (flow, velocity, pressure, and concentration). After evaluation of these, a numerical value was assigned to each pipe, with a range from 1 to 10 (10 being a high level of concern). Each of the parameters was assigned a value, which can be determined or overridden by the user. The program contains guidance for this number system.

- Step 3: Critical Facilities and Population Density. This step involved user selection of critical areas. Pipes in or near critical areas were assigned a value indicating high concern.

The program PipelineNet contains a ranking tool for the EPS simulations done which can serve as a starting point for monitoring location selection. There are different methods for the user to allocate scores based on the system parameters. These are discussed below:

- Natural Breaks: This identifies the break points between different classes of parameters using a statistical formula called Jenk's optimization. This method minimizes the sum of the variance within each of the parameter classes, which can be complex. This basically finds groups or patterns within the data.
- Equal Interval: This method divides the range of parameters into sub-ranges that are equal in size. Then the features are further classified based on those sub-ranges.
- Quantile: This classification method involves classifying the parameters into the same number of classes with the same number of features. These quantiles are best suited for linearly distributed data, other data that does not have disproportionate numbers of features that have similar values.

The user can select any of these three options for any parameter. The values used were only guidance—the user can override any value that is output from the three options. The scores ranged from one to 10, for velocity, pressure, and flow. Thus, each pipe could receive a score up to 30, but scoring could be changed. These values were then displayed in the model. Once in the model, overlay of critical facilities can be done to further

eliminate sites. Figure 6-7 shows the pipes with high scores and also critical infrastructure (hospitals and schools).

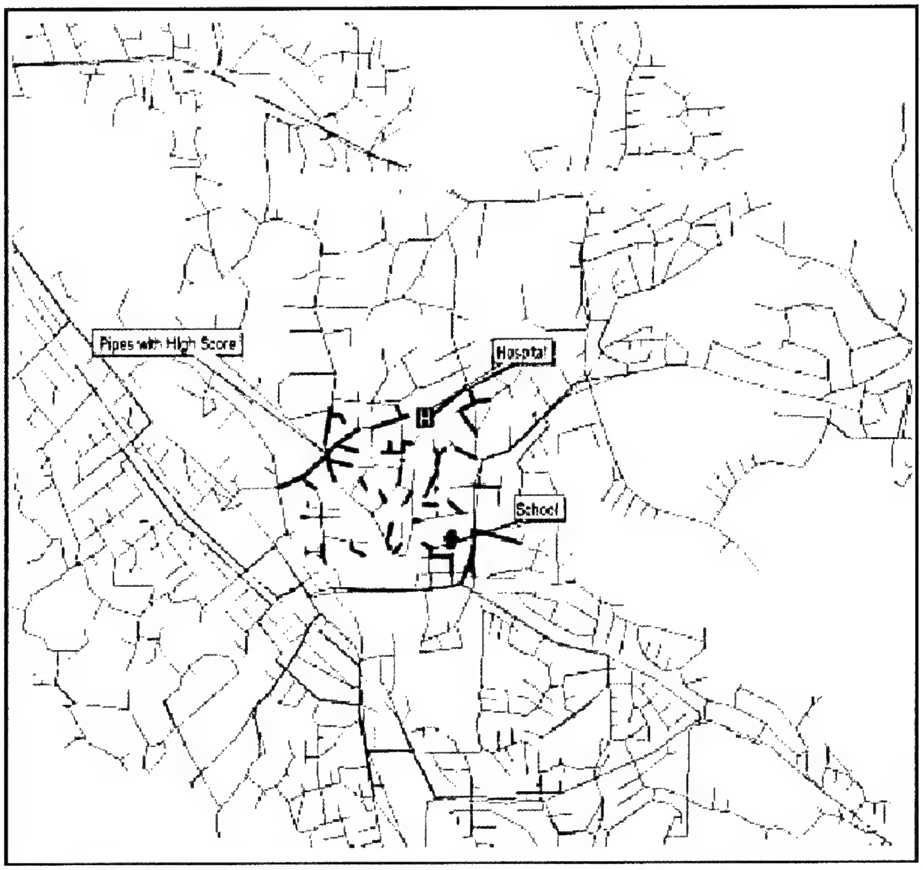


Figure 6-7 PipelineNet system showing high score areas with critical infrastructure.

The case study concluded with the evaluation of consequences, by showing the spread of the contamination from the source, showing the critical facilities and population affected.

<u>Application and use of model.</u>

This case study demonstrated how models can be used to select sites for detector placement. The authors established a hierarchal process to choose the sites and demonstrated this in the model. This process ranked the nodes based on hydraulic parameters based on scores for each. The model used throughout the process to identify

the areas where monitors should be placed. It not only assisted in the selection, but it also was a very useful method to present these decisions as well.

6.5.3 Case Study III.

The next case study was generated specifically as an example of a post-scenario attack and both constituent and trace analyses were conducted using H2OMap™. These analyses would show how the location of the contaminant could be identified and how to confirm a positive event. There would be data constraints in a real world scenario, such as the actual site, contaminant level, pump rate, and various other hydraulic data. In a real world situation, a utility would input any information available into the model. If need be, a contaminant can be assumed to model until more information is obtained.

The hydraulic and chemical constituent information was data normally used in models. The headloss equation was the Hazen-Williams, the accuracy was 0.001, and the water quality tolerance was 0.01. The duration was 24 hours and the hydraulic, pattern, and quality time steps were set at one minute. The clock start time was set at 00:00:00 (midnight), i.e., the contaminant was introduced at midnight. The contaminant modeled was sodium fluoroacetate (1080). One thousand pounds of the contaminant was pumped into the system at a specified node (number 342) using a low flow pump. Table 6-3 lists the reaction coefficients that were used in the model for the chemical.

Table 6-3 Reaction coefficients used in the model.

Global Bulk	-0.002
Global Wall	0
Global Pipe Bulk Reaction Order	1
Global Pipe Wall Reaction Order	0
Global Tank Reaction Order	1
Limiting Potential	0
Roughness Correlation Coefficient	0

Constituent Analysis.

The first post-scenario analysis conducted was constituent analysis. From experiments conducted at Colorado State University, it has been found that sodium fluoroacetate can be detected at levels of 3 mg/L using normally measured water quality parameters. The model was then used to estimate the flow areas of the contaminant.

Figures 6-8 through 6-15 were generated from the model. Each of these figures show two key pieces of information in their contour lines. The yellow line is the LD_{50} line (240 mg/L). This value was calculated by Allman, using an assumed amount of water ingested by an average sized man (Allman, 2003). The red line is the point in the system where the contaminant would be 3 mg/L or greater, the detectable level according to the experiments. The figures depict the contaminant travel at times of 1, 3, 6, and 12 hours. Each time increment has two distinct figures—one of the entire distribution system and one that is zoomed in of the site that contamination was entered.

Figure 6-8 Contaminant travel after 1 hour, full view.

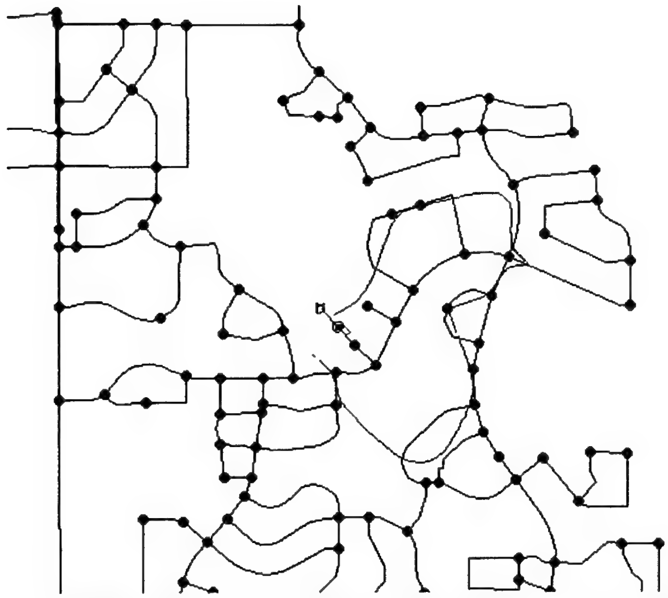


Figure 6-9 Contaminant travel after 1 hour, close view.

Figure 6-10 Contaminant travel after 3 hours, full view.

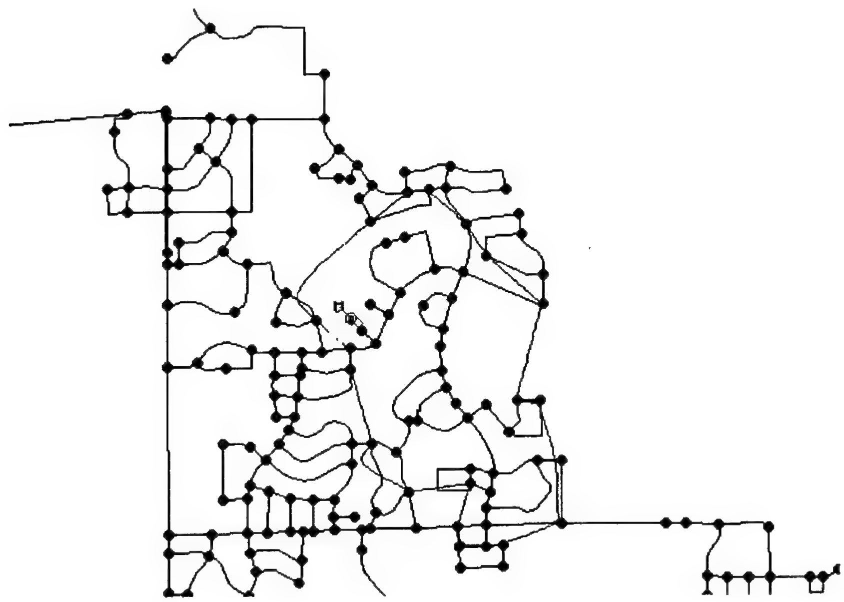


Figure 6-11 Contaminant travel after 3 hours, close view.

Figure 6-12 Contaminant travel after 6 hours, full view.

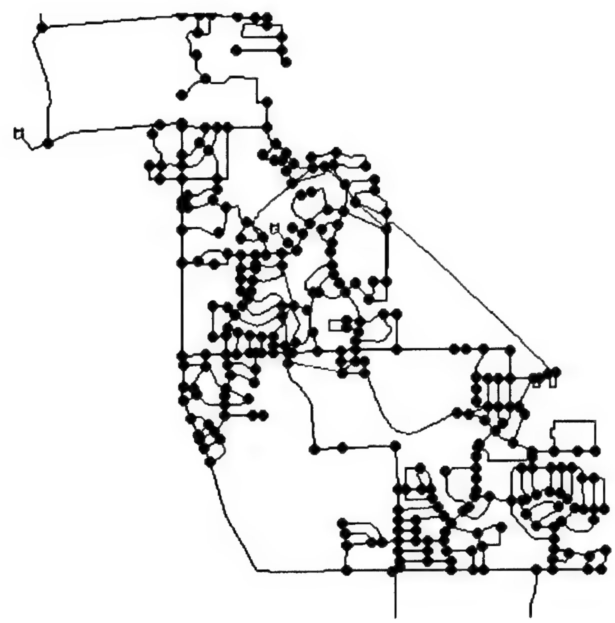


Figure 6-13 Contaminant travel after 6 hours, close view.

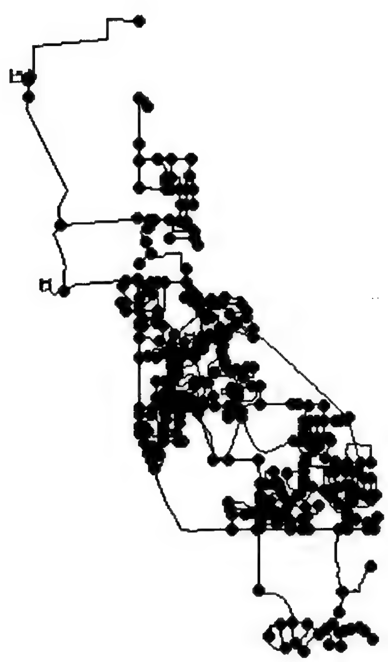


Figure 6-14 Contaminant travel after 12 hours, full view.

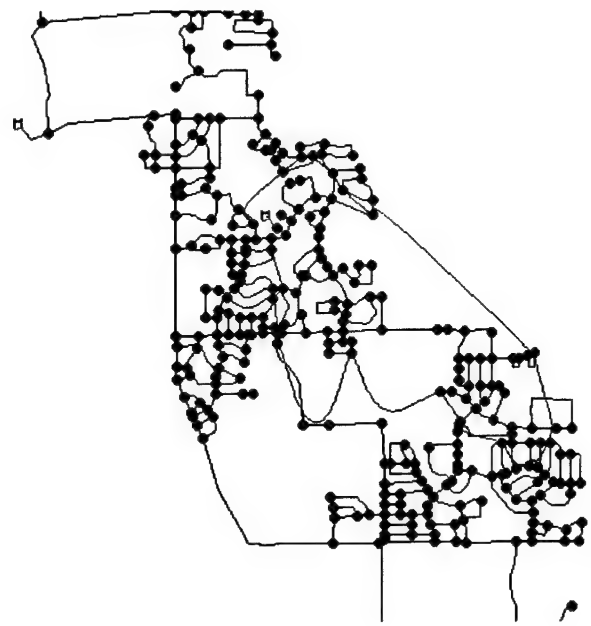


Figure 6-15 Contaminant travel after hours, close view.

This analysis using the chemical constituent shows the area where the chemical exceeds the detection level and the LD_{50} levels. This shows where the contaminant can impact customers. It can also show where the contaminant will travel. This can be used to help determine not only where corrective actions can be taken, but also where additional samples can be taken to ensure there was an actual contamination event.

Trace Analysis:

The next analysis completed was a source trace analysis for node 342, which is the node where the contaminant was entered. The same model was used with the same data. This analysis can be very useful to determine what other nodes would be impacted by the contamination. The contaminant was injected at node 342, which was then used as the trace node. These numbers will change significantly based on hydraulic factors of the

system, including the demand patterns. The time of 0800 hours was arbitrarily chosen to present for this case study. Note that only those nodes impacted by the contaminant are listed.

Table 6-5 shows the nodes that were impacted by the water from the trace node, which is represented as a percentage. Again, this information would be extremely useful because the amount of water impacted by the contaminant is shown.

Table 6-4 Trace analysis of contaminated node.

Node	% 342 (%)	Node	% 342 (%)	Node	% 342 (%)
343	100.00	432	62.41	614	42.54
342	100.00	433	62.41	615	42.52
344	100.00	431	62.40	623	41.74
346	100.00	602	62.29	624	40.90
348	100.00	452	61.56	631	39.08
347	100.00	456	60.99	611	28.95
345	100.00	601	60.31	378	23.15
446	80.85	600	59.64	373	23.14
448	63.21	603	57.06	550	19.07
451	63.16	555	55.24	388	16.01
445	63.10	551	51.17	552	13.13
454	62.96	607	49.81	556	10.70
442	62.92	604	48.92	632	10.33
444	62.81	612	48.91	634	6.12
450	62.80	606	48.71	387	3.43
455	62.72	447	48.52	377	3.43
443	62.41	453	48.16	541	0.16
441	62.41	613	47.21	542	0.15
440	62.41	605	46.02	516	0.14
435	62.41	630	44.30	386	0.13
430	62.41	610	44.02	553	0.02
434	62.41	620	42.80	543	0.01

<u>Application and use of model</u>

This case study demonstrates several key aspects of model application after a scenario has occurred. The first main aspect is confirmation of a positive event. Drastic

actions would not be taken at the first positive, but confirmation would then begin. A model would be an extremely powerful tool in this because it can show where the contaminant would be expected to travel. This can show when it would reach another monitor or it could show where to send workers to go and take samples in the field. The second major aspect is identifying the location of contamination. The source node can be designated, and then other areas impacted can be determined. This source node does not need to be the actual source and could be the area where the contaminant was first detected. Other nodes throughout the system that were impacted by the contamination can then be identified for further action.

CHAPTER 7. RESULTS AND DISCUSSION: MODELING OF MICROBIOLOGICAL CONTAMINANTS

The case studies showed how modeling has been used for chemical constituents in various capacities. These modeling efforts were based on accidental chemical contamination with known decay rates. There has not been research into the detection of microbiological contamination using these normally measure water quality parameters. Because of this data gap, research was done to determine if *Cryptosporidium parvum* could be detected through these parameters. If the oocysts could be detected, this could significantly improve water security. The data from this research was then analyzed through a water modeling program.

7.1 Beaker Tests

The primary goal of the beaker tests was to determine the level of the *Cryptosporidium parvum* oocysts that could be detected before the system tests were run. The detection would be based on the changes from the tap water quality, so the tap water was analyzed also. The first concentration analyzed was 250 oocyts/0.5 L. From the literature review, the lowest ingested exposure found to cause infection ranges from 132 to 239 oocysts, but that it is possible to be lower, even down from 10 to 30. These exposures were based on ingestion, which would be approximately 0.5L of water. It was determined that a concentration of 250 would be a good starting point to determine if the level could be detected using the parameters selected.

After the initial test of 250 oocysts/0.5 L was measured, additional readings were taken at the concentrations listed in Table 7-1.

Table 7-1 Date analyses completed.

Concentration (oocysts/0.5L)	Date analyzed
16	11 November
100	6 November
250	11 November
250	3 November
1,000	4 November
5,000	13 November
5,000	6 November
50,000	13 November
50,000	10 November

Tables 7-2 through 7-6 contain the data for each water quality parameter. The tables show the values for the tap water, the sample water with the oocysts, and the change in the reading. Appendix 3 contains the data from each day that the tests were run.

Table 7-2 Chlorine analyses.

Concentration (oocysts/0.5L)	Tap Water	Oocysts	Change
16	0.61	0.6	-0.01
100	0.52	0.48	0.04
250	0.56	0.53	0.03
1,000	0.58	0.51	0.07
5,000	0.56	0.54	0.02
50,000	0.58	0.44	0.14

Table 7-3 Turbidity analyses.

Concentration (oocysts/0.5L)	Tap Water	Oocysts	Change
16	0.43	0.55	0.12
100	0.77	0.17	0.60
250	0.51	0.17	0.34
1,000	1.1	0.17	0.93
5,000	0.78	0.18	0.60
50,000	0.35	0.18	0.17

Table 7-4 TOC analyses.

Concentration (oocysts/0.5L)	Tap Water	Oocysts	Change
16	1.31	1.31	0
100	1.42	1.45	-0.03
250	1.31	1.35	-0.04
1,000	1.24	1.29	-0.05
5,000	1.42	1.43	-0.01
50,000	1.24	1.3	-0.06

Table 7-5 pH analyses.

Concentration (oocysts/0.5L)	Tap Water	Oocysts	Change
16	7.86	7.85	-0.01
100	7.75	7.72	0.03
250	7.75	7.74	0.01
1,000	7.74	7.68	0.06
5,000	7.76	7.69	0.07
50,000	7.76	7.76	0

Table 7-6 Conductivity analyses.

Concentration (oocysts/0.5L)	Tap Water	Oocysts	Change
16	121	121	0
100	127	124	3
250	124	117	7
1,000	127	124	3
5,000	127	123	4
50,000	123	122	1

This data was then graphed to show the differences between the tap water and the samples with the oocysts. Three different graphs were used because of the data ranges. Figure 7-1 shows that the change in TOC increased as oocyst concentration increased, while pH and chlorine residual decreased. Note that the difference change was approximately equal for the three parameters, but TOC was positive and pH and chlorine residual were negative. The oocyst concentration in these figures was graphed as logs of the concentration.

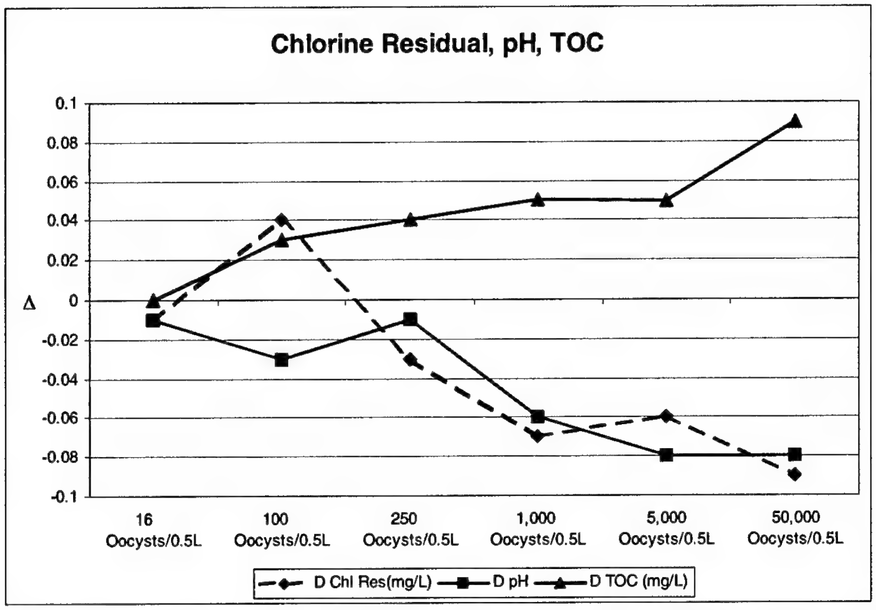


Figure 7-1 Chlorine residual, pH, and TOC changes tap water from sample with oocysts.

Figure 7-2 shows the change in turbidity. The figure does not show any significant pattern.

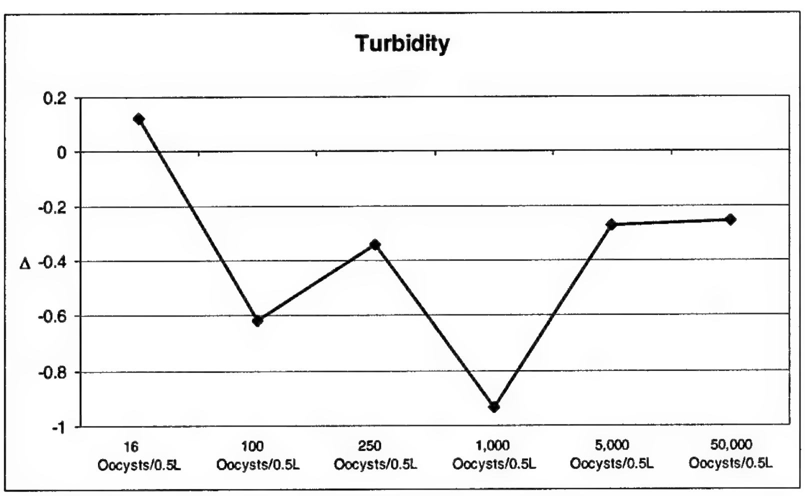


Figure 7-2 Turbidity changes for tap water with oocysts.

Figure 7-3 shows the change for conductivity. Again, it does not show any continuous trend.

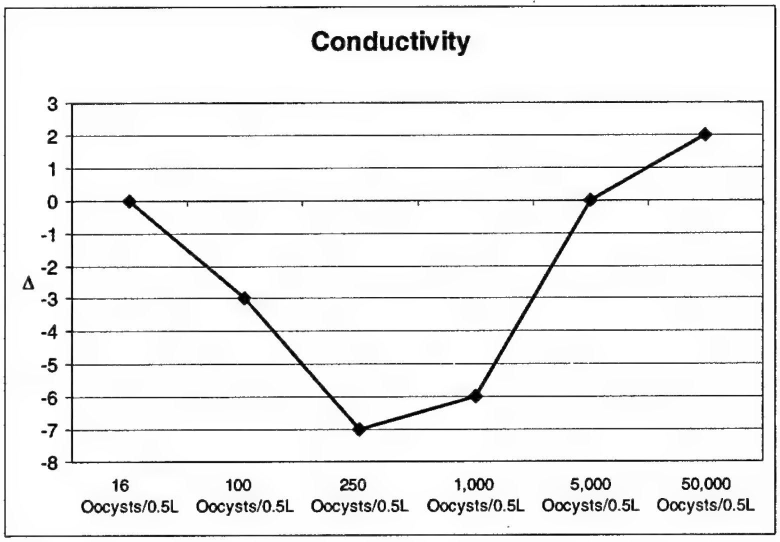


Figure 7-3 Conductivity changes for tap water with oocysts.

It was expected that turbidity would be the best measure of the oocysts in the sample, but because the data was inconclusive, the turbidity readings were re-accomplished on December 1. The same concentrations were re-sampled with the same background tap water, which eliminated the variability due to the tap water. The tap water turbidity was 0.315 NTU and 0.204 NTU, for an average turbidity 0.260 NTU. Table 7-7 displays this data.

Table 7-7 Change in turbidity analyses.

Concentration (Oocysts/0.5L)	Log Concentration	Turbidity Reading 1	Turbidity Reading 2	Average Turbidity Reading	Change in Turbidity
16	1.20	0.26	0.44	0.35	0.090
100	2.00	0.19	0.19	0.19	-0.073
250	2.40	0.26	0.25	0.27	0.005
1,000	3.00	0.24	0.21	0.22	-0.036
5,000	3.70	0.17	0.18	0.18	-0.081
50,000	4.70	0.31	0.27	0.29	0.027

This data was then graphed to show the difference in the turbidity readings, as seen in Figure 7-4. Again, it did not show useful patterns at these concentrations.

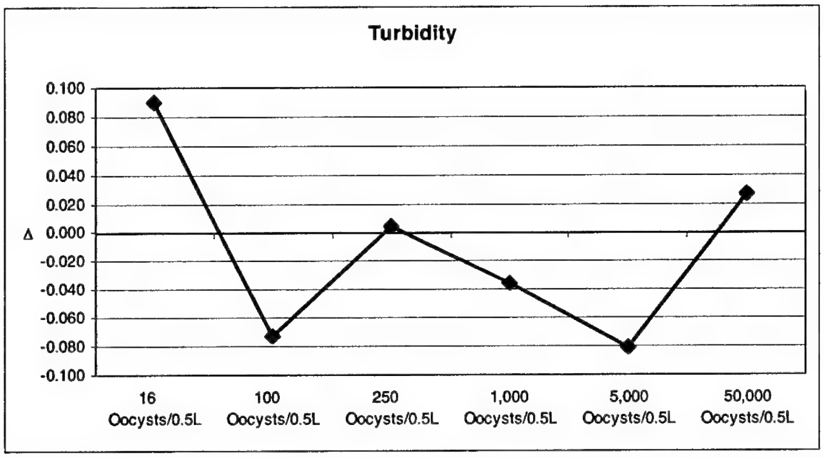


Figure 7-4 Turbidity changes for tap water with oocysts (second analyses)

Based on the data obtained from the beaker tests, it was concluded that the water quality parameters could not detect the contaminant at a low enough concentration to prevent illnesses. It was expected that turbidity and TOC would be the most likely parameters that would measure the oocysts; however, neither of these proved reliable readings. Based on this, the distribution systems started at significantly higher concentrations.

7.2 System Distribution Tests

The next step was the distribution system tests. The beaker tests showed that the levels of oocysts would not be detectable at levels less than 50,000/0.5 L. Based on this, higher concentrations were analyzed in these tests, starting with 100,000 oocysts/0.5L. Table 7-8 shows the concentrations and dates the system tests were analyzed.

Table 7-8 Date system analyses completed.

Concentration (oocysts/0.5L)	Date analyzed
100,000	19 November
200,000	21 November
400,000	8 January
600,000	9 January

Turbidity, laser turbidity, TOC, chlorine residual, pH, and conductivity were measured for each concentration. TOC, turbidity, laser turbidity, and chlorine residual were analyzed statistically. Conductivity and pH did not reveal any meaningful data, nor were they expected to, so they were excluded from the statistical analysis. This statistical analysis included calculation of the average, sigma, and 3-sigma, which were calculated using Microsoft Excel. The upper detection level is the 3-sigma value added to average and the lower detection value is the 3-sigma value subtracted from the average. The average is the mean of the baseline data for each day data was collected, which was the first 100 minutes of data collection. The 3-sigma is the detection level, that is, any reading above or below this level is considered abnormal and would be detectable using these instruments. Based on this, the parameter measured must be above (or below) the 3-sigma baseline value in order for the oocysts to be detected. Tables 7-9 through 7-12 lists these statistical analyses for each of the concentrations measured using the distribution tests.

Table 7-9 Statistical analysis of 100,000 oocyst/0.5L.

	TOC (mg/L)	Turbidity (NTU)	Laser Turbidity (NTU)	Chlorine Residual (mg/L)
Average	1.53	0.11	0.47	0.48
σ	0.0062	0.0056	0.31	0.0044
3σ	0.019	0.017	0.93	0.013
Upper level	1.55	0.13	1.40	0.49
Lower Level	1.51	0.096	-0.46	0.47

Table 7-10 Statistical analysis of 200,000 oocyst/0.5L.

	TOC (mg/L)	Turbidity (NTU)	Laser Turbidity (NTU)	Chlorine Residual (mg/L)
Average	1.63	0.073	0.093	0.62
σ	0.0084	0.00076	0.11	0.0050
3σ	0.025	0.0023	0.32	0.015
Upper level	1.65	0.075	0.41	0.64
Lower Level	1.60	0.071	-0.23	0.61

Table 7-11 Statistical analysis of 400,000 oocyst/0.5L.

	TOC (mg/L)	Turbidity (NTU)	Laser Turbidity (NTU)	Chlorine Residual (mg/L)
Average	1.77	0.17	0.15	0.48
σ	0.012	0.046	0.10	0.026
3σ	0.037	0.13	0.31	0.079
Upper level	1.81	0.31	0.46	0.56
Lower Level	1.73	0.030	-0.16	0.40

Table 7-12 Statistical analysis of 600,000 oocyst/0.5L.

	TOC (mg/L)	Turbidity (NTU)	Laser Turbidity (NTU)	Chlorine Residual (mg/L
Average	1.74	0.095	0.14	0.36
σ	0.0070	0.0077	0.14	0.0050
3σ	0.021	0.023	0.41	0.015
Upper level	1.76	0.12	0.55	0.37
Lower Level	1.72	0.072	-0.27	0.34

The data for these concentrations was graphed. The graphs have three red lines. The top and bottom lines are for the upper and lower levels of detection, respectively. The middle red line, which is dashed, is the average for the baselines. Note that in some graphs there is no bottom red line. In these cases, the lower level of detection was negative, which cannot be possible based on these parameters; therefore, it was excluded in these analyses.

These statistical analyses were based on a calculated 100-minute baseline from the tap water. This time was long enough to allow the system to reach equilibrium but it was not long enough to establish a baseline not impacted by the changes in a single day's water quality. This means that the readings for one day may have data ranges not normally seen, which will then have detrimental effects on the detection methods used in this research. For example, the statistical analyses for the 200,000/0.5L showed that the upper level detection would be 0.075 NTU and the lower level would be 0.071 NTU. This was based on how close the turbidity data was for turbidity that day. The statistical analyses for the 400,000 oocysts/0.5L shows something very different. The upper level detection limit was 0.31 NTU and the lower level was 0.03 NTU. Based on the calculated baseline, it would be much more difficult to detect the oocysts with the baseline for the 400,000 oocysts/0.5L. This is discussed more in-depth later.

Figures 7-5 through 7-8 include the data for the concentration of 100,000 oocysts/0.5L.

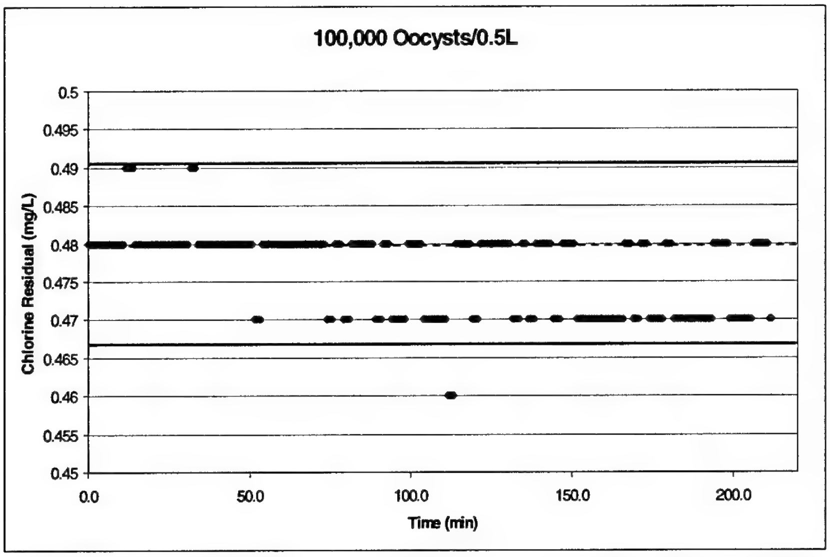


Figure 7-5 100,000 oocysts/0.5L change in chlorine residual.

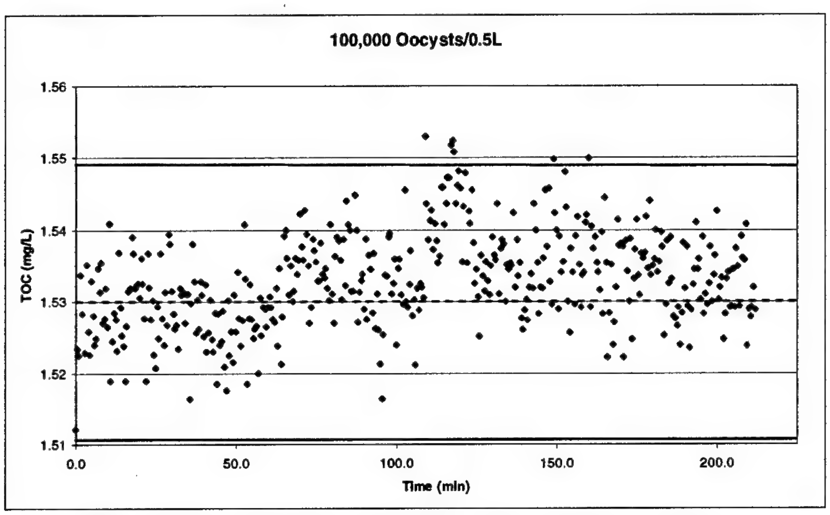


Figure 7-6 100,000 oocysts/0.5L change in TOC.

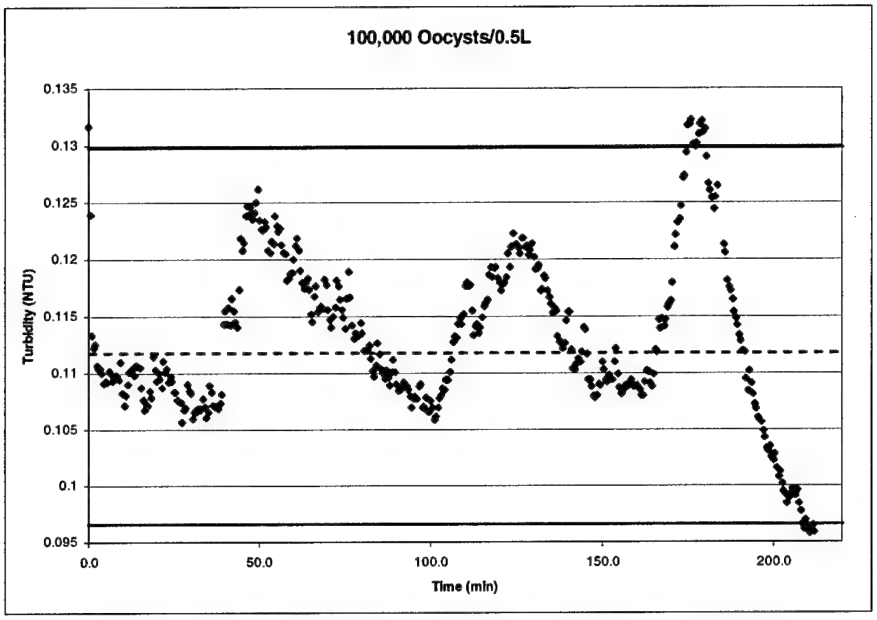


Figure 7-7 100,000 oocysts/0.5L change in turbidity.

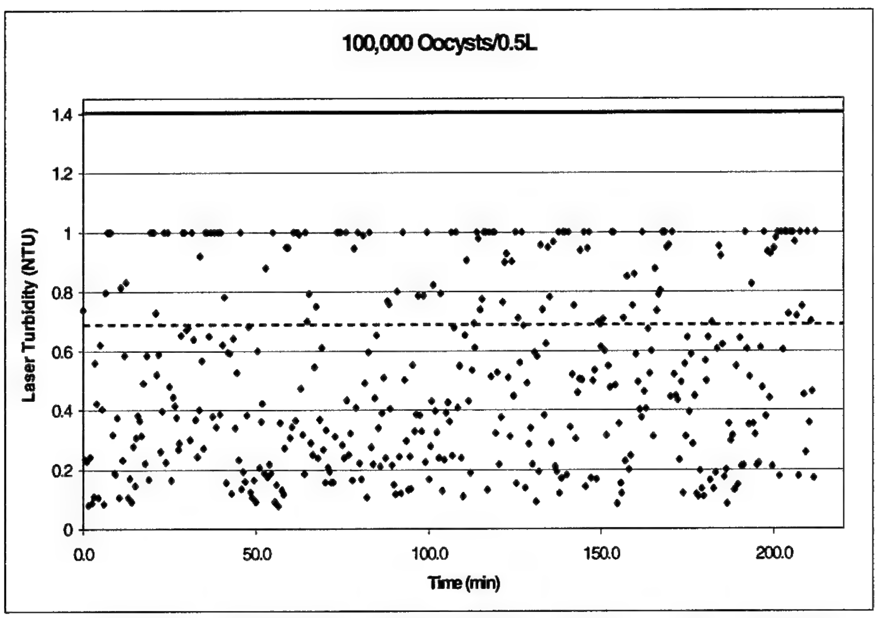


Figure 7-8 100,000 oocysts/0.5L change in laser turbidity.

These figures show that the concentration of 100,000 oocysts/0.5L cannot be detected through these measurements. The chlorine readings were within the upper and lower detection limits except for one data point. The TOC data were above the upper

detection level for several readings, but only for a few data points. The figure for turbidity showed several spikes; however, closer review shows that these are not useful. Note that one spike occurred before the contaminant was added and the second spike was below the 3-sigma level. The final spike was above the 3-sigma level, but it was after the point in time when the contaminant would have reached the detector. Finally, the laser turbidity was very erratic and no useful information can be taken from it. These graphs showed that the concentration of 100,000 oocysts/0.5L cannot be measured through these parameters.

Figures 7-9 through 7-12 show the data for the 200,000 oocysts/0.5L concentration.

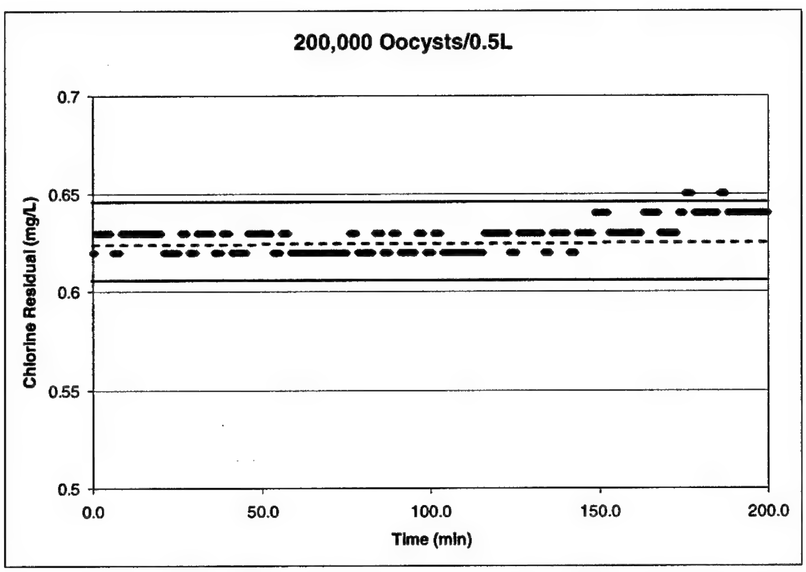


Figure 7-9 200,000 oocysts/0.5L change in chlorine residual.

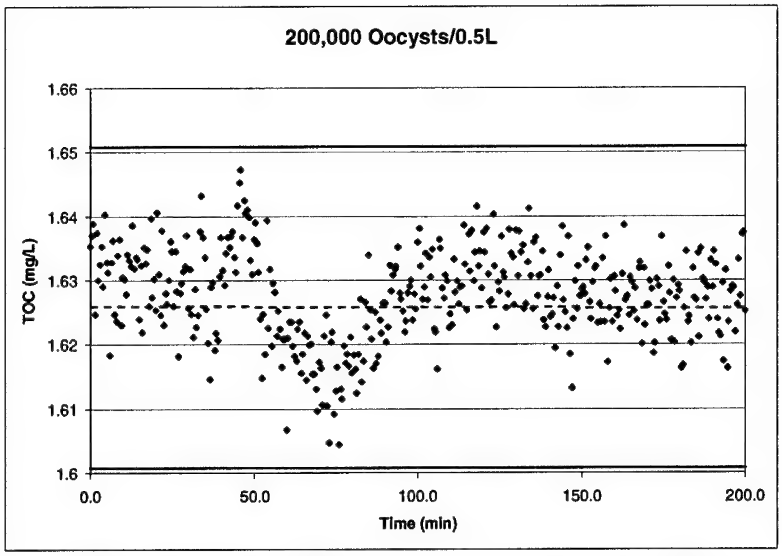


Figure 7-10 200,000 oocysts/0.5L change in TOC.

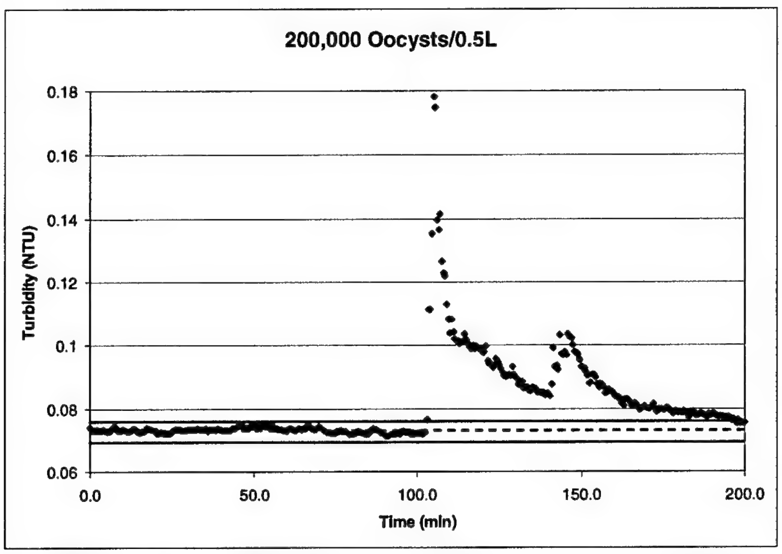


Figure 7-11 200,000 oocysts/0.5L change in turbidity.

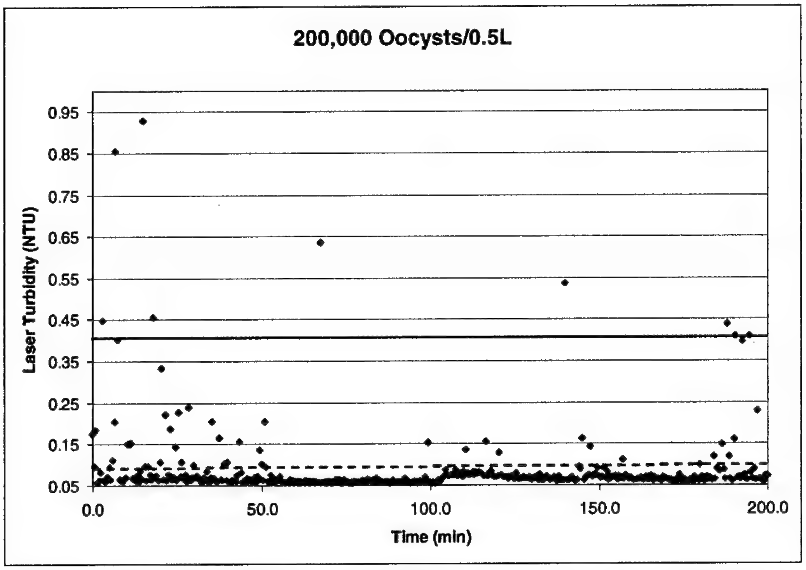


Figure 7-12 200,000 oocysts/0.5L change in laser turbidity.

The chlorine residual graph showed that this could not be used for detection because there were no readings outside the 3-sigma values. The same is true for the TOC. There was a spike in turbidity that exceeded the upper level, thus turbidity could be used to detect this concentration. The laser turbidity did not show any useful information for this concentration. Based on this, the 200,000 oocysts/0.5L concentration can be detected using these parameters.

Figures 7-13 through 7-15 show the data for the 400,000 oocysts/0.5L concentrations. Note that chlorine residual is not included because it did not provide useful information for the previous concentrations.

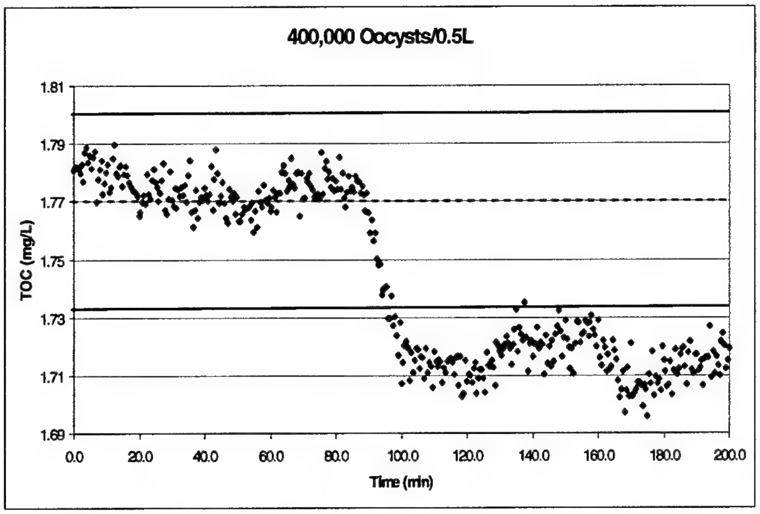


Figure 7-13 400,000 oocysts/0.5L change in TOC.

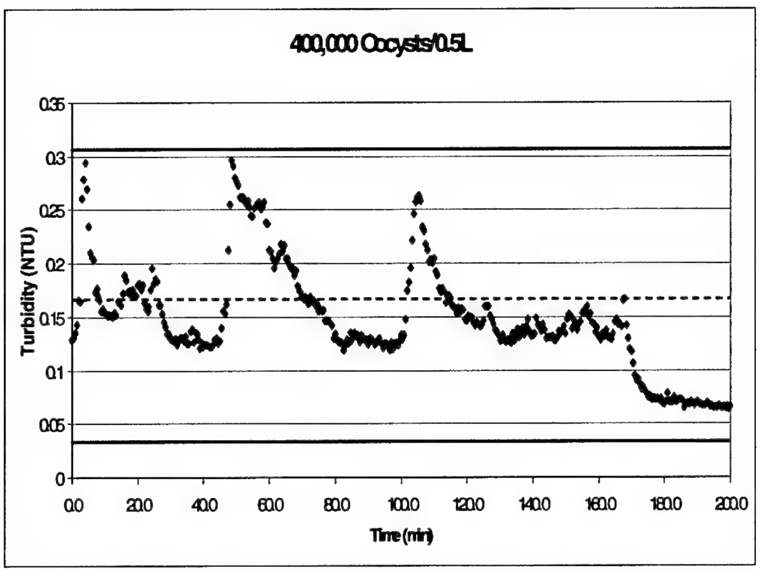


Figure 7-14 400,000 oocysts/0.5L change in turbidity.

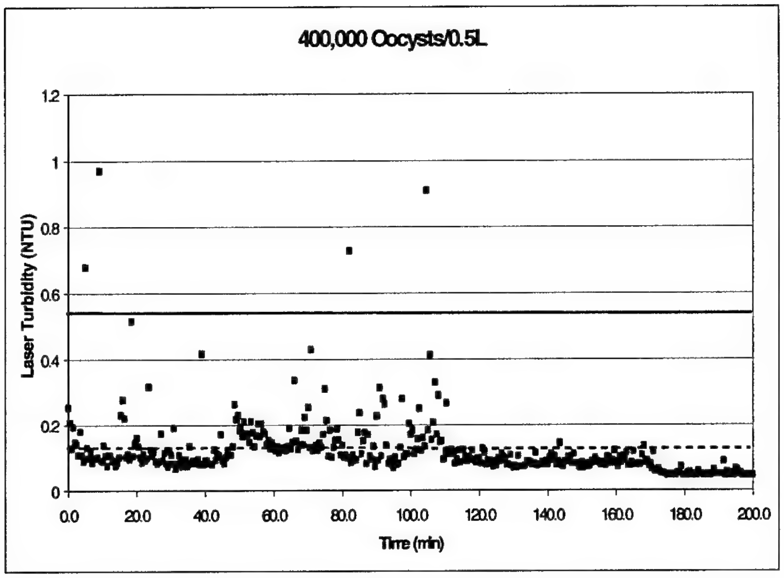


Figure 7-15 400,000 Oocysts/0.5L change in laser turbidity.

Figure 7-13 for TOC showed an interesting trend—the TOC actually decreased as the oocysts were added, which is opposite of what was expected and seen in the other concentrations. The drop in TOC was below the 3-sigma value so theoretically it could be used to detect the oocysts at this concentration. The reason for this drop was not known. The turbidity data showed a spike after the oocysts were introduced into the system, but it did not cross the upper level detection limit because of the large 3-sigma value. The reason for this higher 3-sigma value was because of the turbidity spikes in the baseline before the oocysts were introduced. The cause for the spike during the baseline was unknown and could have been caused by conditions at the water treatment plant. This problem could be overcome in a system with more data analysis, which would be more likely to remedy any anomalies or otherwise abnormal data. Note that laser turbidity again did not provide useful information.

Figures 7-16 through 7-18 are the graphs of the data for the 600,000 oocysts/0.5L.

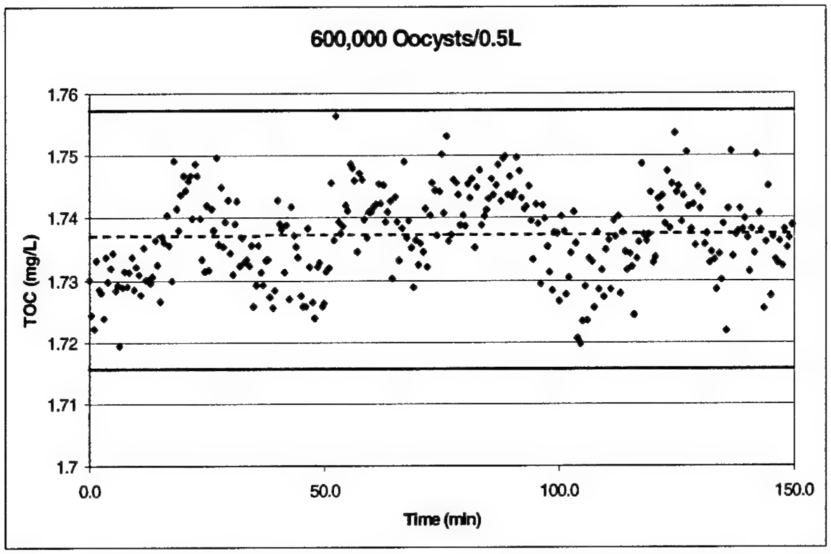


Figure 7-16 600,000 Oocysts/0.5L change in TOC.

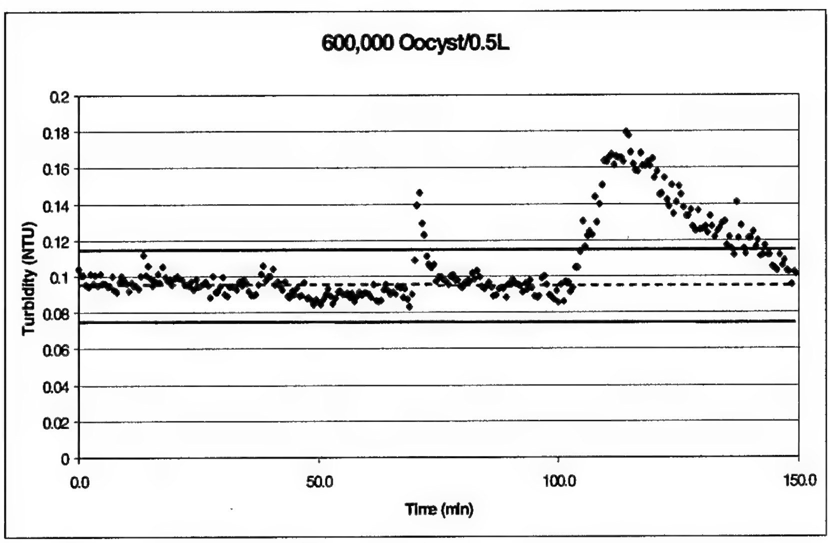


Figure 7-17 600,000 oocysts/0.5L change in turbidity.

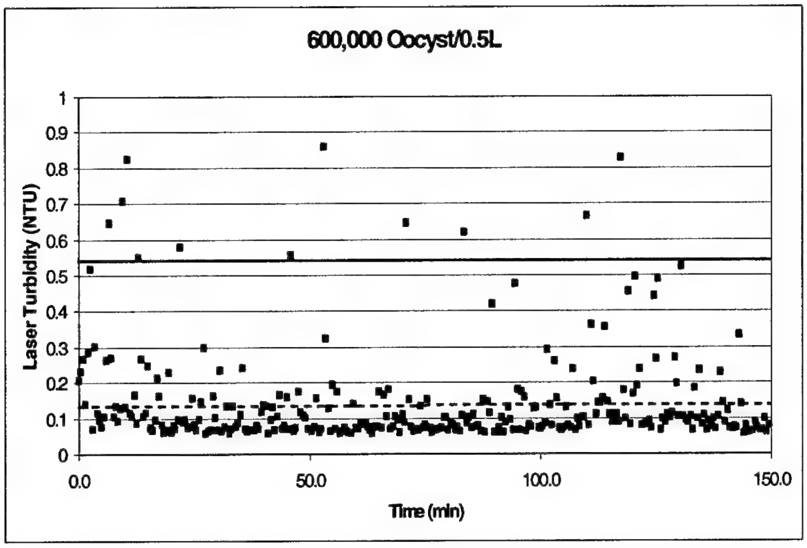


Figure 7-18 600,000 Oocysts/0.5L change in laser turbidity.

The figures show that TOC and laser turbidity did not provide useful information for this concentration. The values for turbidity did exceed the upper detection level. Note that there was one spike before the oocysts were added. It was not known why this occurred. This showed that the 600,000 oocysts/0.5L can be detected using turbidity. This was not as sensitive as the 200,000 oocysts/0.5L because the 3-sigma value was higher for the 600,000 oocysts/0.5L concentration..

Table 7-13 includes a summary of the detection capabilities based on the data analyzed.

Table 7-13 Summary of detection capabilities for given concentration.

Concentration (Oocysts/0.5L)	Chlorine Residual	TOC	Turbidity	Laser Turbidity
100,000	No	No	No	No
200,000	No	No	**Yes[1]**	No
400,000	No	**Yes[2]**	**No[3]**	No
600,000	No	No	**Yes[1]**	No

1—Turbidity readings after contaminant introduced were above the 3-sigma level.
2—TOC readings after contaminant introduced were below the 3-sigma level.
3—Turbidity showed expected spike as contamination was entered, but based on large 3-sigma values, readings did not exceed the detection level.

Based on the data, the best method to detect the oocysts is turbidity. The turbidity readings were above the 3-sigma level for both the 200,000 oocysts/0.5L and 600,000 oocysts/0.5L concentrations. Turbidity for 100,000 oocysts/0.5L and 400,000 oocysts/0.5L concentrations had spikes after the oocysts were added but they did not exceed the 3-sigma levels. The turbidity readings for the 400,000 oocysts/0.5L concentration did not exceed the upper level detection limit based largely on the large 3-sigma value. The 100,000 oocysts/0.5L concentration showed a spike as the concentration was added, but it was not as distinguishable from the baseline readings as the other oocysts levels. The actual turbidity readings increased in a somewhat systematical manner as the concentration was increased. The only exception for this was the 400,000 oocysts/0.5L concentration, which did increase, but increased at a larger value than the other concentrations.

Laser turbidity and chlorine residual did not offer any useful information. There were no real changes for the TOC after the oocysts were added except for the100,000 oocysts/0.5L and 400,000 oocysts/0.5L concentrations. The TOC actually decreased at the 400,000, but the reason for this was unknown. There were several readings just outside the 3-sigma level for the 100,000 oocysts/0.5L concentration, but there were not enough points to make it a meaningful detection.

This analysis shows that the detectable limit for the oocysts is approximately 200,000 oocysts/0.5L using these parameters and the best parameter to measure would be turbidity. The data analysis method used in this research demonstrates that this contaminant can be detected using these water quality parameters; however, the detection

limit is based largely on the baseline, which determines the 3-sigma level. A larger background sample would help alleviate this problem.

7.3 Modeling Results

The oocyst data was then modeled using H2OMap™. The current water distribution system modeling programs are designed to model chemical constituents, and not necessarily microbiological contamination. There are two options for modeling microbiological contaminants. First, trace analysis can be used. This would only show where the contaminant traveled from the source node selected. Second, chemical constituent analysis can be used. This is designed specifically for chemicals; however, it can be used for microbiological contaminants if they are assumed to be conservative. Based on the chlorine resistance of this oocyst, this is a valid assumption.

The contaminant must be entered into H2OMap™ as a concentration in either mg/L or μg/L, which is not the normal concentration for a microorganism. The correlation of oocyst density is that 3 oocysts/m^3 is equivalent to 0.0002 ng/liter (Thompson and Smith, 2001). The mass concentration was then calculated for several oocyst concentrations.

$$\frac{3 \text{ oocysts}}{\text{m}^3} = \frac{0.0002 \text{ ng}}{\text{Liter}}$$

This was then converted to more traditional water measurement units.

$$\frac{0.003 \text{ oocysts}}{\text{liter}} = \frac{2 \times 10^{-7}\ \mu\text{g}}{\text{Liter}}$$

Theses values were then converted from the oocysts/L to the μg/L based on selected oocyst concentration. Table 7-14 displays these values.

Table 7-14 Conversion from oocyst to mass concentration.

Concentration (oocysts/0.5L)	Concentration (oocysts/liter)	Concentration (μg/L)
10	5	0.000333
30	15	0.00100
132	66	0.00440
239	120	0.00797
1,000	500	0.0333
5,000	2,500	0.167
50,000	25,000	1.67
100,000	50,000	3.33
200,000	100,000	6.67
400,000	200,000	13.3
600,000	300,000	20.0
1,000,000	500,000	33.3

Based on the data analysis, the detection limit was 200,000 oocysts/0.5L or 100,000 oocysts/L.

Contour lines were then established to show the spread of the contaminant. The contours lines were completed to show where the infective doses would be found as well as the areas where the contaminant would be detected. The contour lines are show in Table 7-15.

Table 7-15 Model contour lines showing concentrations.

Concentration (μg/L)	Concentration (oocyst/0.5L)	Contour Color
0.01*	300	
1.67	50,000	
6.67	200,000	
33.33	1,000,000	

*This was the lowest concentration contour available for input into H2OMap™.

The modeling was then completed. Four different scenarios were modeled and the figures are attached. These scenarios are summarized below.

Scenario 1	Low flow pump in neighborhood
Scenario 2	Low flow pump in neighborhood
Scenario 3	Low flow pump on large water main
Scenario 4	High flow pump on large water main

Each of these scenarios is described in-depth below. These graphs were developed through H2OMap™. Each graph has several components of the water system. Each green circle is a system demand. These are groupings of water customers that can include businesses, residences, etc. These nodes are connected by pipes, which are represented by blue lines within the model. The figures are presented geographically, that is, the top of the figures is north. For this particular system, the water treatment plant is in the far northwest corner of the model. To show the information properly, the view is zoomed into the area of contamination. Based on this, the water plant is not seen for scenarios 1 and 2. The general pattern of water flow is from the water treatment plant in the northwest, down to the southeast.

7.3.1 Scenario 1: Low flow Pump within Neighborhood

Scenario 1 was a low flow pump within a residential area. Table 7-16 shows the dosage and pumping information. Table 7-17 shows the contour lines used in the figures.

Table 7-16 Scenario 1 dosage and pumping information.

Pump rate	0.1	gpm
Volume pumped	5	gallons
Pumping time	50	minutes
Pump location	Inside neighborhood	
Oocyst mass	0.4	kg
Oocyst concentration	21,130,000	μg/L

Table 7-17 Model contour lines showing concentrations.

Concentration (μg/L)	Concentration (oocyst/0.5L)	Contour Color
0.01	300	
1.67	50,000	
6.67	200,000	
33.33	1,000,000	

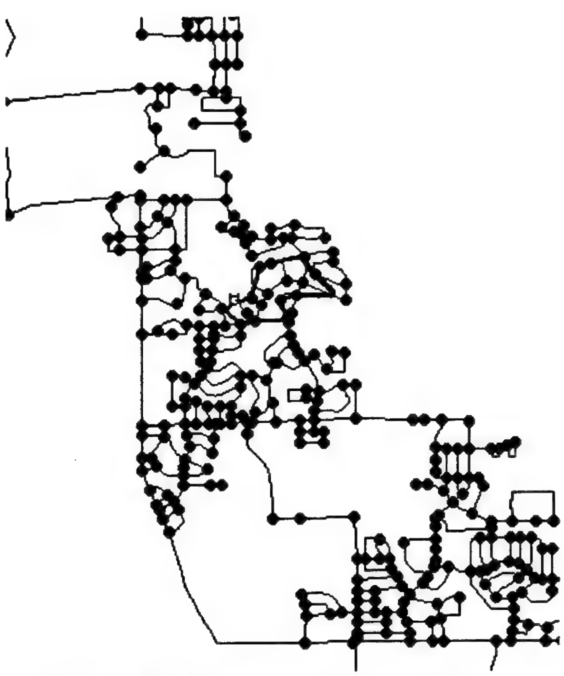


Figure 7-19 Scenario 1 oocysts spread at 0100 hours.

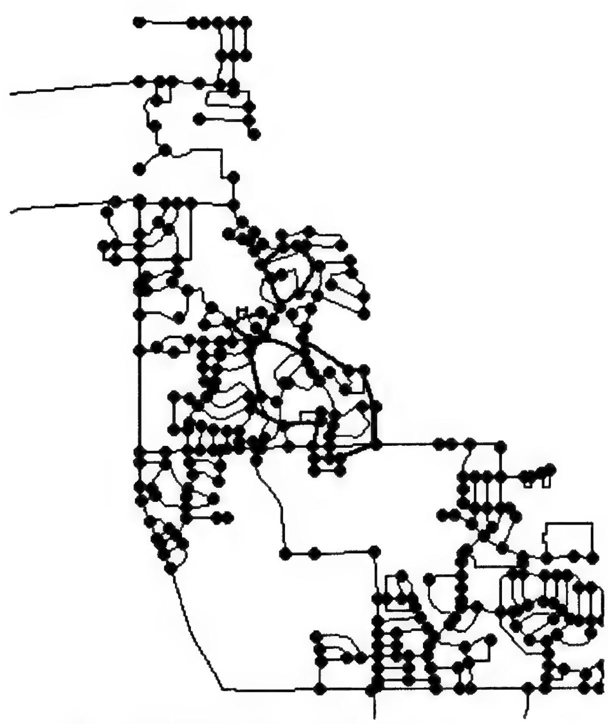


Figure 7-20 Scenario 1 oocysts spread at 0300 hours.

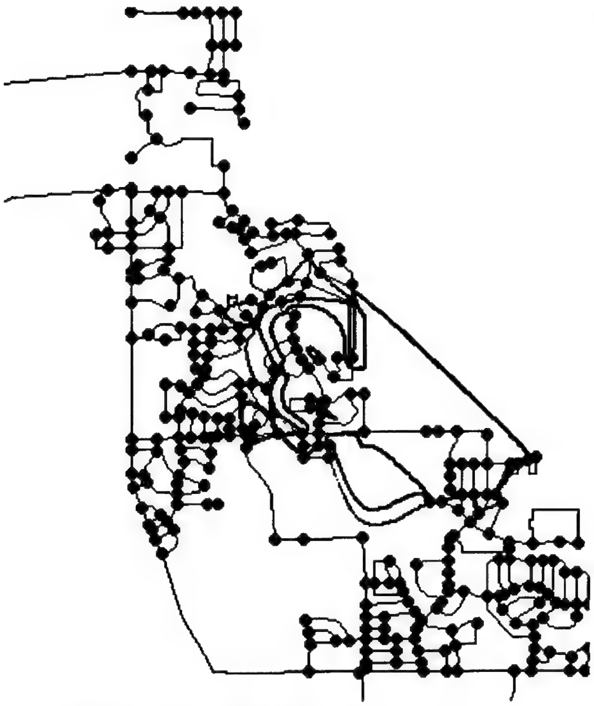


Figure 7-21 Scenario 1 oocysts spread at 0600 hours.

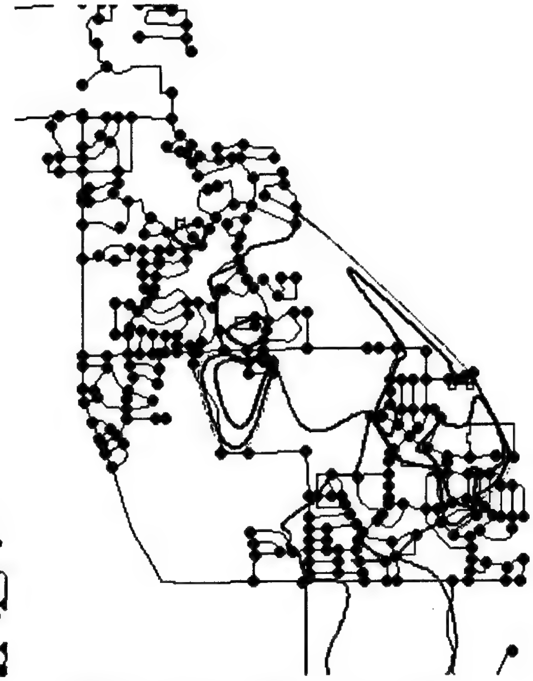


Figure 7-23 Scenario 1 oocysts spread at 1800 hours.

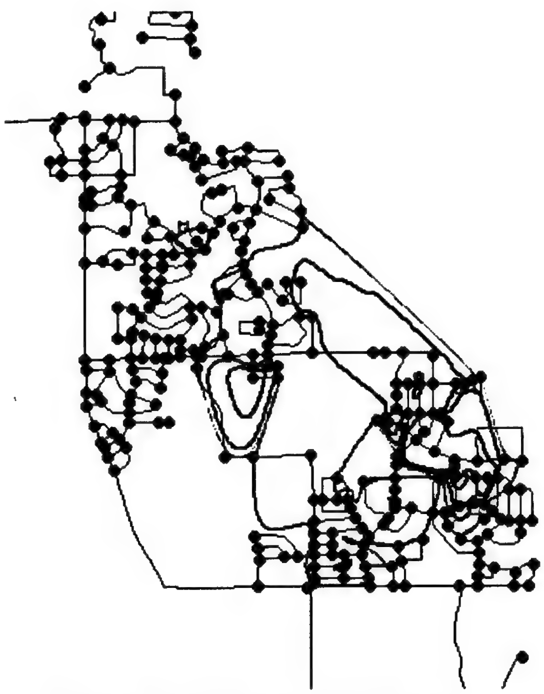


Figure 7-22 Scenario 1 oocysts spread at 1200 hours.

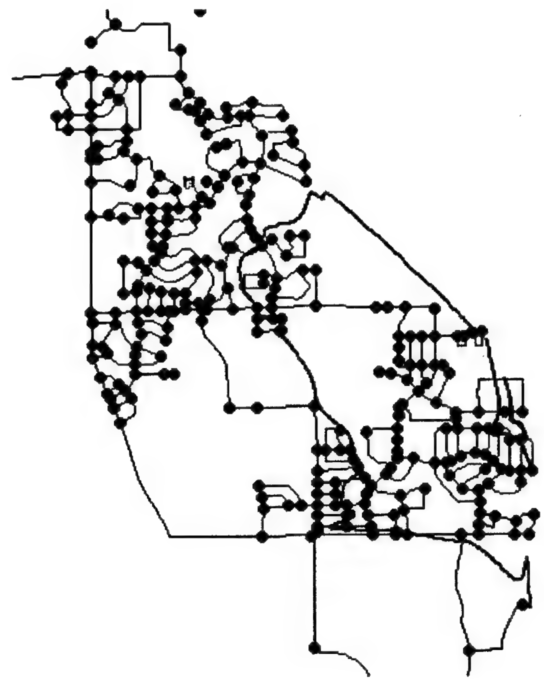


Figure 7-24 Scenario 1 oocysts spread at 2400 hours.

The figures show the expected spread of the contaminant at various times throughout the day. Figure 7-19 shows that even after 1 hour, the spread has

impacted a large area of the system. The contaminant at this point is only seen at levels of 1,000,000 oocysts/0.5L. The pattern changes at 0300 hours when it forms two distinct pockets. These pockets of contamination join together again by 0600 hours. Figure 7-21 shows that the pattern is still spreading at 0600 hrs, and the actual levels are decreasing with some areas below 200,000 oocysts/0.5L. The contaminant continues to spread throughout the rest of the day with some areas still at 1,000,000 oocysts/0.5L and some areas much lower, down to 300 oocysts/0.5L. After 24 hours, the contaminant has been largely diluted, but the areas the contaminant passed through are still at 300 oocysts/0.5L, with a very large impacted area.

Overall this shows that the contaminant, if injected in this manner, would be detected if monitors were placed within those areas. The entire area for the first 6 hours has concentrations of up to 200,000 oocysts/0.5L, which was the lowest detection level. These levels did begin to deteriorate at the end of the day and were well below the detection level at the end of the day.

7.3.2 Scenario 2: High Flow Pump within Neighborhood

Scenario 2 was a high flow pump within a residential area. Table 7-18 shows the dosage and pumping information. Table 7-19 shows the contour lines used in the figures.

Table 7-18 Scenario 1 dosage and pumping information.

Pump rate	10	gpm
Volume pumped	50	gallons
Pumping time	5	minutes
Pump location	Inside neighborhood	
Oocyst mass	0.4	kg
Oocyst concentration	2,113,000	μg/L

Table 7-19 Model contour lines showing concentrations.

Concentration (μg/L)	Concentration (oocyst/0.5L)	Contour Color
0.01	300	
1.67	50,000	
6.67	200,000	
33.33	1,000,000	

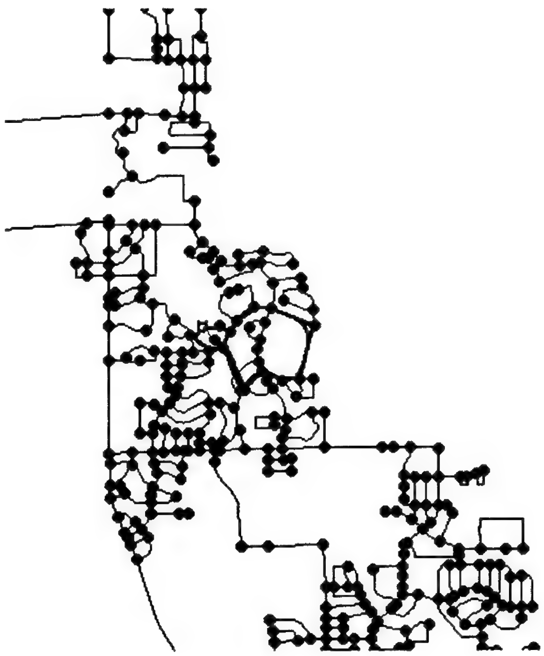


Figure 7-25 Scenario 2 oocysts spread at 0100 hours.

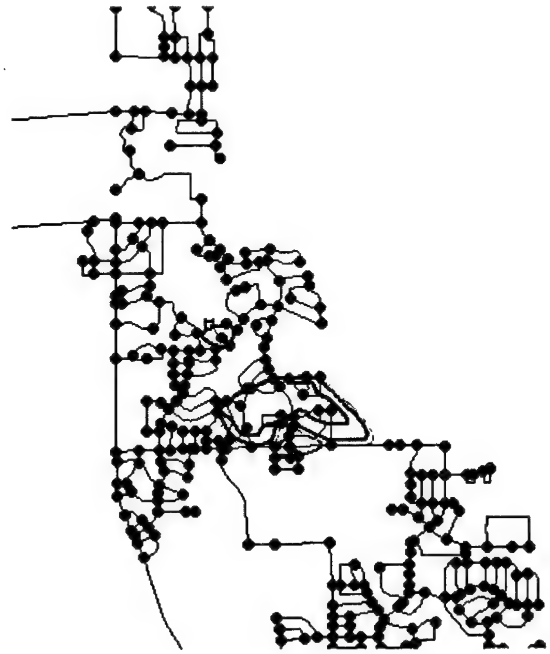


Figure 7-26 Scenario 2 oocysts spread at 0300 hours.

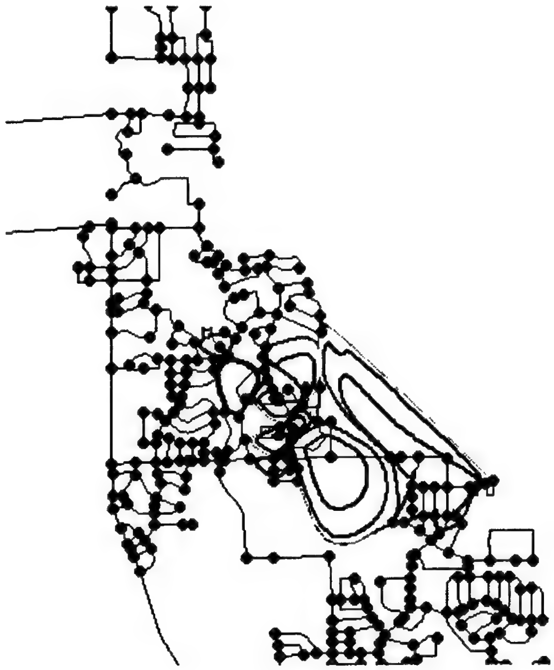


Figure 7-27 Scenario 2 oocysts spread at 0600 hours.

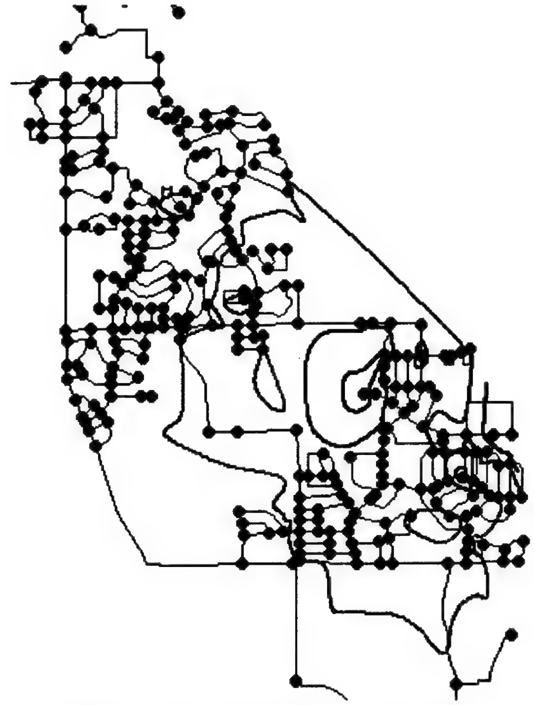


Figure 7-29 Scenario 2 oocysts spread at 1800 hours.

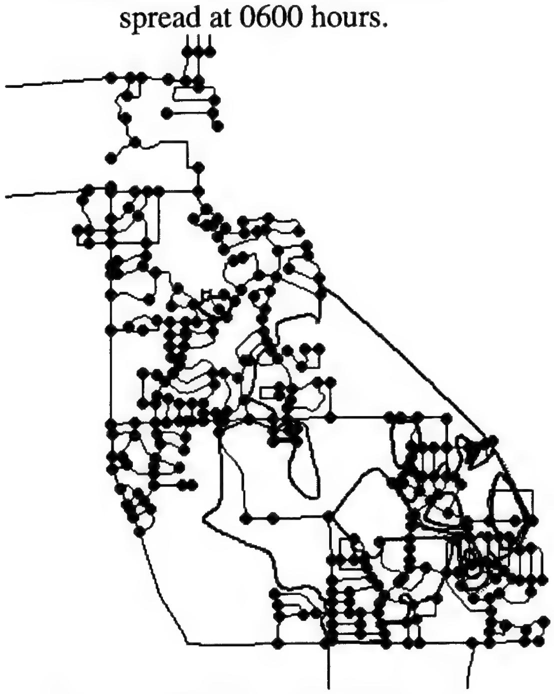


Figure 7-28 Scenario 2 oocysts spread at 1200 hours.

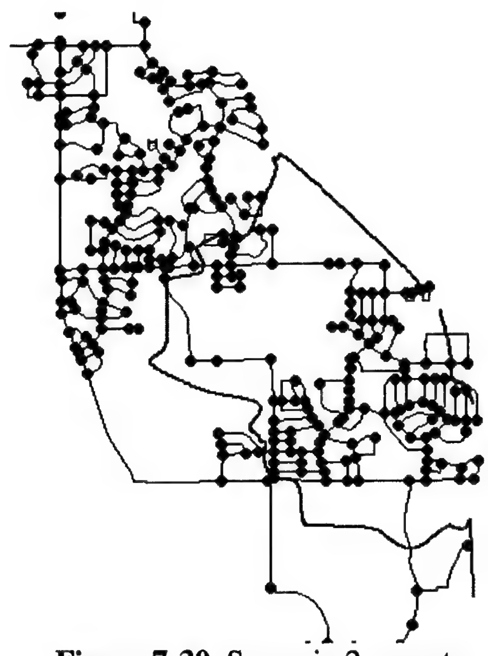


Figure 7-30 Scenario 2 oocysts spread at 2400 hours.

Scenario 2 showed similar results to scenario 1 with a few exceptions. First, the contaminated area was smaller at 0300 hours for this scenario. There were also

areas of lower concentrations at this time, but concentrations of 200,000 oocyts/0.5L did travel through these areas so it was still detectable. These figures do not show an actual distinction between two pockets, but evaluating the diagram for 0600 shows that there probably were two distinct pockets at some point between 0300 and 0600 hours. The same similar area was contaminated at 0600 for both scenarios; however for this scenario the contaminant again had areas where the concentration was much lower, down to 300 oocysts/0.5L at some points. At times 1800 and 2400 hours, the same basic contamination patterns were seen as with scenario 1, but there were lower concentration along the outer edges.

The conclusions that can be made are that the low flow and high flow contaminant roughly the same area, but that the contaminant decreases in concentration more quickly for the high flow pump. All these areas were still above the infective dose. Based on this, the low flow pump scenario would be easier to detect because of the higher concentrations traveling through the system. Both scenarios showed the same approximate contamination areas, but scenario 1 spread contamination further to the north and scenario 2 spread it further to the south.

7.3.3 Scenario 3: Low Flow Pump on Water Main

Scenario 3 was a low flow pump on a large water main. Table 7-20 shows the dosage and pumping information. Table 7-21 shows the contour lines presented in the figures.

Table 7-20 Scenario 1 dosage and pumping information.

Pump rate	0.1	gpm
Volume pumped	5	gallons
Pumping time	50	minutes
Pump location	Large water main	
Oocyst mass	0.4	kg
Oocyst concentration	21,130,000	µg/L

Table 7-21 Model contour lines showing concentrations.

Concentration (µg/L)	Concentration (oocyst/0.5L)	Contour Color
0.01	300	
1.67	50,000	
6.67	200,000	
33.33	1,000,000	

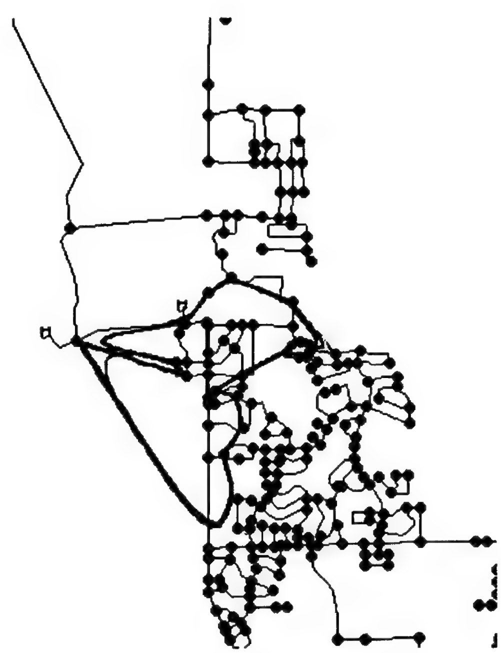


Figure 7-31 Scenario 3 oocysts spread at 0100 hours.

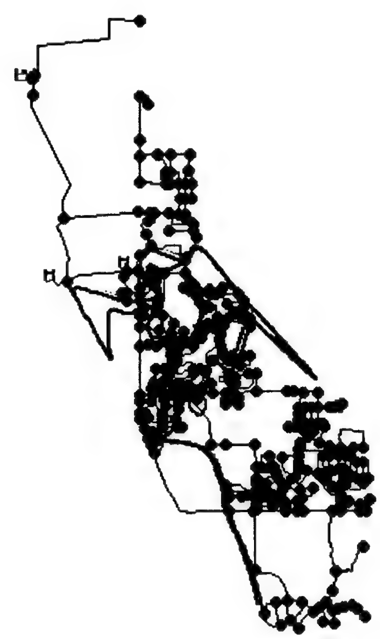


Figure 7-32 Scenario 3 oocysts spread at 0300 hours.

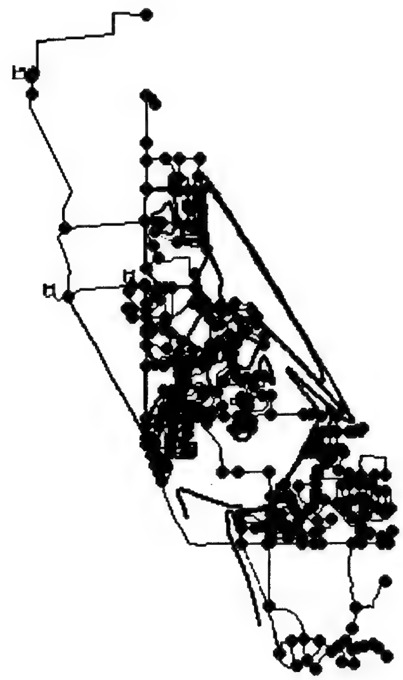


Figure 7-33 Scenario 3 oocysts spread at 0600 hours.

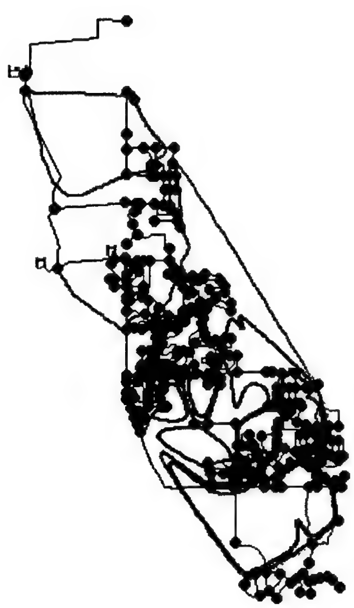


Figure 7-34 Scenario 3 oocysts spread at 1200 hours.

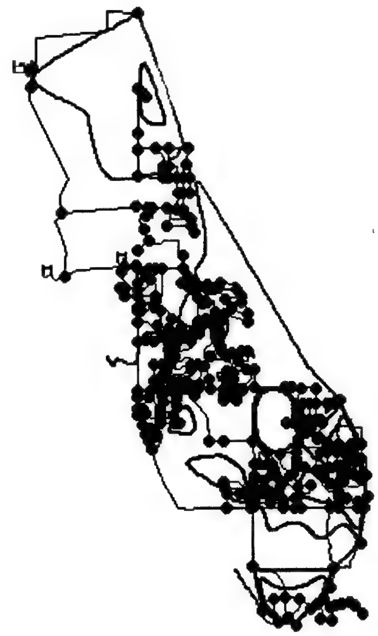


Figure 7-35 Scenario 3 oocysts spread at 1800 hours.

Figure 7-36 Scenario 3 oocysts spread at 2400 hours.

Scenario 3 showed an overall much higher contamination rate than the previous two scenarios. This started with a large area immediately at 0100 hours, with concentrations of 1,000,000 oocysts/0.5L. This contamination continued to spread through the system at 0300 hours at levels of 200,000 or higher. The spread continued at 0600 but there were areas at a concentration of 300 oocysts/0.5 L level as well. There were no individualized pockets of contamination seen throughout these times. The spread continued to the southeast in these higher concentrations. The same was true at 1200 hours, but there were levels of 300 that went to the northwest as well. The same pattern held for the rest of the day, that is the bulk of the spread continued to the southeast with areas at 300 at the north part of the system. It is interesting that at the 1800 hours there was one area at the north part of the system that was at 200,000. The graphs show that nearly the entire system is impacted at levels up to 300 oocysts/0.5L at least at one point in less than one day. Most of this contamination would be above the 200,000 oocysts/0.5L level, so it would be detected.

7.3.4 Scenario 4: High Flow Pump on Water Main

Scenario 4 was a high flow pump on a large water main. Table 7-22 shows the dosage and pumping information. Table 7-23 shows the contour lines used in the figures.

Table 7-22 Scenario 1 dosage and pumping information.

Pump rate	10	gpm
Volume pumped	50	gallons
Pumping time	5	minutes
Pump location	Large water main	
Oocyst mass	0.4	kg
Oocyst concentration	2,113,000	µg/L

Table 7-23 Model contour lines showing concentrations.

Concentration (μg/L)	**Concentration (oocyst/0.5L)**	**Contour Color**
0.01	300	▬▬▬
1.67	50,000	
6.67	200,000	▬▬▬
33.33	1,000,000	▬▬▬

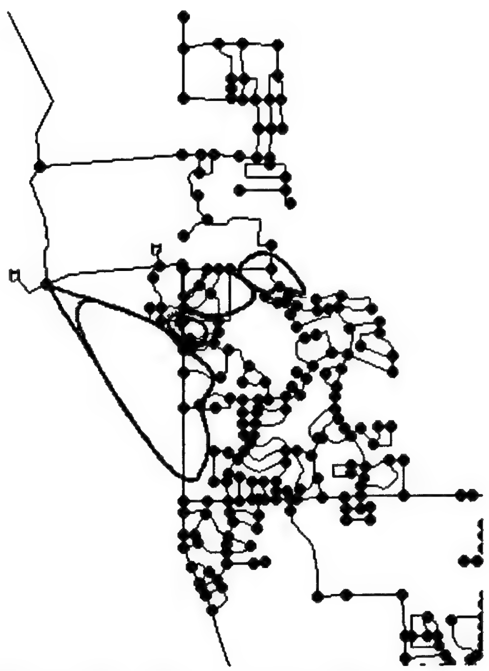


Figure 7-37 Scenario 4 oocysts spread at 0100 hours.

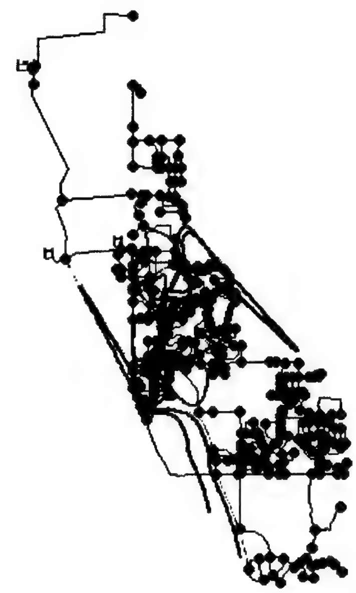


Figure 7-38 Scenario 4 oocysts spread at 0300 hours.

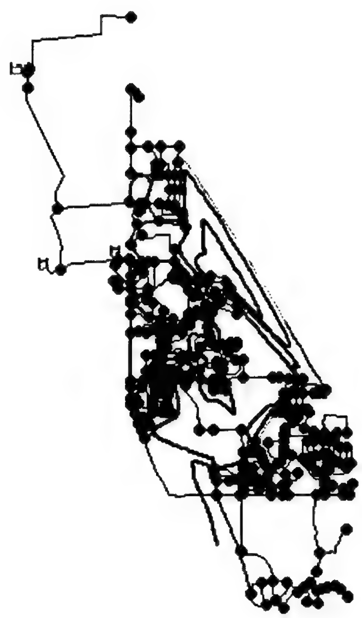


Figure 7-39 Scenario 4 oocysts spread at 0600 hours.

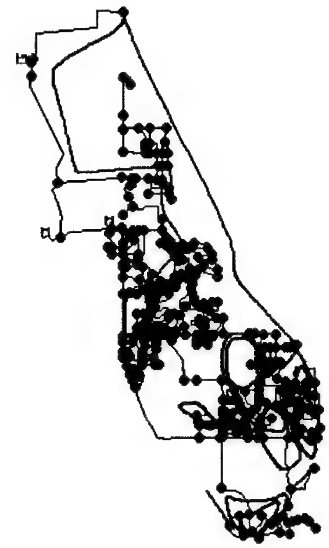


Figure 7-41 Scenario 4 oocysts spread at 1800 hours.

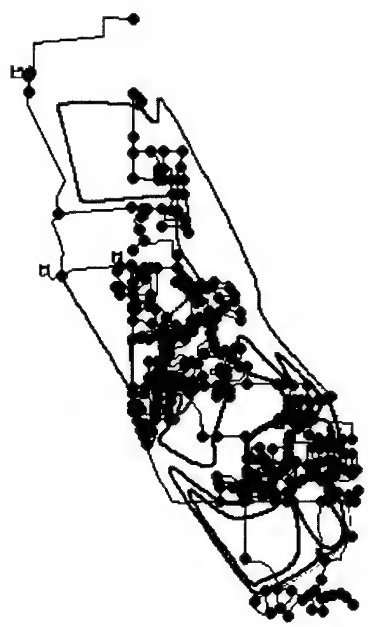


Figure 7-40 Scenario 4 oocysts spread at 1200 hours.

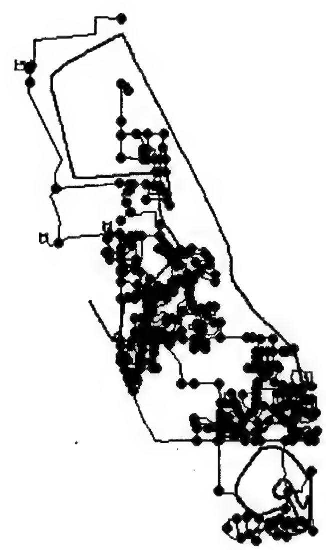


Figure 7-42 Scenario 4 oocysts spread at 2400 hours.

The figures for scenario 4 show a different concentration pattern at 0100 than scenario 3 in that there were four distinct pockets of contamination. All the concentrations at this point were above the detection level. The contamination pattern at

0300 hours was similar to that same time in scenario 3, but much lower concentrations were seen, down to 300 oocysts/0.5L. There is similar type of contamination pattern compared to scenario 3. Again, nearly the entire system had contamination at some points above the infectivity level of 300 oocysts. This scenario, like scenario 3, showed that the contamination moved in large concentrations to the southeast, leaving behind lower concentrations as the bulk of the water moved. These concentrations left behind were below the detection limits, but still above the infective dose. The contamination for this scenario did not go as far north as scenario 3, but did contaminate the same approximate area.

7.4 Contamination Detection

As was expected, the location of the contaminant injection had a large impact on the spread. All four scenarios impacted the system to a large degree, but the scenarios within the neighborhoods were more localized. The scenarios on the water mains had a much larger impact, with nearly every area above the infective dose at some point. Based on the contaminant spread, there would be a large population infected but it would be detected using the normally measured water quality parameters.

Trace analysis could also be done for this type of contamination. This would show what nodes would have received water from the contaminated node. This would provide limited information, i.e., no concentration, but would provide very useful information to the public health officials.

This analysis did show weaknesses of current indirect detection methods. Microbiological contaminants may not be able to be detected until people exhibiting symptoms begin to visit clinics. This could be as long as the incubation period, which

according to the AWWA can be from 5 to 28 days, with a mean of 7.2 days, but depends largely on the immune status of the host (AWWA, 1999b).

CHAPTER 8. CONCLUSIONS

The results of the modeling show that large-scale contamination of a drinking water system may be accomplished through introduction of microbiological contaminants through backflow. The research showed that the oocysts could be detected at 200,000 oocysts/0.5L, which is well above the highest infective dose of 239 oocysts. This detection method is based largely on a baseline of the water system, thus if there is a significant amount of variability in the water quality parameters then the detection limit could be significantly higher. If this methodology were to be used in a real water system, this variability could be minimized through on-going statistical analyses calculating the 3-sigma level. The modeling showed that using four different scenarios, the contamination would be detected, but after many people were possibly already exposed. This demonstrates that detection of microbiological contaminants should have a much higher priority in water security issues.

Four different backflow scenarios were analyzed. These included pumping the contaminant in two different areas, using two differing pumps in each area. The locations included one area within a neighborhood and another much closer to a main line. The pumps used included a low flow and high flow. There was much more system contamination when the contaminant was pumped in on the main line. When the main line was used to pump water into the system, nearly the entire system had concentrations above the infective does. The pump rates and concentrations of the contaminants

impacted the spread, but not as significantly as the location. The results showed that successful covert attacks would not necessarily require detailed knowledge of the system. An attack using *Cryptosporidium parvum* oocysts would not likely result in large loss of life, but would greatly impact the health of nearly everyone consuming the water as well as resulting in a significant loss of confidence in the water.

The research also showed that commonly used water quality tools can be applied to water security issues. Guidance for modeling application to security was developed. The modeling can be applied in four basic guidelines: model development, pre-scenario analysis, post-scenario analysis, and detector placement evaluation. The guidance developed can help any utility size develop a model for security purposes. Additionally, commonly used monitoring equipment can be used to detect the spread of *Cryptosporidium parvum*. The detection, while not able to detect a low concentration, can and will show when the system has been contaminated. This can allow a utility to begin to take proper precautions. The applications of these tools can allow water utilities to increase their security. Because the contamination would be detected through these normally measured water quality parameters, there could be many of these monitors placed within the system. They could also be placed at the entry of highly vulnerable targets, such as hospitals, schools, and government buildings. This type of monitoring would not reveal the contaminant, but it would immediately notify the utility if there was a problem. Additional monitoring would then be required, but it would begin the confirmation process.

Overall, this research showed the vulnerabilities of water utilities to one microbiological contaminant. More research is needed to decrease these vulnerabilities,

but through the application of normally used water distribution tools, water utilities can enhance their security.

CHAPTER 9. RECOMMENDATIONS FOR FURTHER RESEARCH

The results of this research showed that *Cryptosporidium parvum* oocysts can be detected using normally measured water quality parameters, but the detection level was significantly higher than the infective dose. Considering the modeling data that demonstrated this could be used to contaminate a water system, further research could focus on decreasing this level of detection.

This research was based on the assumption that the infective dose would be given to an individual at one sitting, thus the volume assumed was 0.5 L. The actual consumption patterns of the water users are crucial to determining the impact. Future studies could focus on the consumption patterns and how they will impact the infections.

The analysis completed in this thesis could be applied to other microbiological contaminants. These pathogens could include *Bacillus anthracis*, *Salmonella typhi*, *Clostridium perfringens*, and the rugose strain of *Vibrio cholerae*. Surrogates are available for some of these pathogens, which would allow the research to be completed in a university environment. The same research could be applied to biotoxins as well, including botulinum toxin and ricin. Additional biosafety measures may be required for some of these, which may preclude such work from being completed at a university.

Another research item could include conducting the same research on impure biological contaminants. The *Cryptosporidium parvum* oocysts used for this research were pure and in de-ionized water. A saboteur may not use oocysts that are pure, and

thus there could be many other chemicals or other impurities with the oocysts. It may be difficult to determine the exact nature of these impurities unless there are specific chemicals that are used to induce certain life stages of the organism. If these impurities could be identified, they could be included in the oocysts and the detection limit may be lowered.

Another area for further research is modeling microbiological contaminants. This research showed that there is a vulnerability associated with microbiological contaminants. The modeling was completed using the chemical constituent capabilities in the model, which was adequate but based on the model limitations, the lowest infective doses could not be modeled. Model codes could be changed to include methods to model microbiological contaminants. The *Cryptosporidium parvum* oocysts are very resistant to chlorine, which made it very conducive to modeling because it was assumed to be conservative. Other pathogens are impacted by chlorine. Additional research could focus on the inactivation rates of these pathogens so that they can be modeled.

Another potential area for further research would be more of a tactical modeling analysis that is to look at these flows more on a small-scale approach. This would include evaluating the vulnerabilities of specific buildings to attack. Specific buildings would include schools, hospitals, nursing homes, and certain government buildings. There are some models that allow a targeted area to be analyzed. This analysis would also allow evaluation of specific measures taken at these locations, such as point of use treatment and monitoring for specific sites.

The guidance presented in this thesis for the response is geared towards determining where the contaminant is and focusing immediate responses, such as

notification and system flushing. The literature has some information on how to decontaminate a system, but this is very limited. Additional information for the post-scenario response would be extremely useful for post-response action.

Another potential detection is through the medical community, that is, patients beginning to exhibit symptoms and then consequently seeking treatment. Another method would be the purchase of certain over-the-counter drugs at drugstores, such as anti-diarrhea products. Monitoring of these purchases should be included in any surveillance program.

This research showed that water distribution modeling software can be very useful in security applications, both before and after an event would occur. Water utilities should consider implementing modeling programs as a method to enhance their security.

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APPENDICES

Appendix 1: Model Database

BRANCH 3.0 / LOOP 4.0

Developed by the University of North Carolina	Download from: Environmental Management 105, Hanuman Industrial Estate 42, G.D. Ambekar Road, Wadala Mumbai - 400 031, India Tel : 91 22 24168217 / 2413 9125 Fax : 91 22 2413 9125 Internet: http://www.emcentre.com/

General Description: BRANCH 3.0 and **LOOP 4.0** are programs that were developed by the University of North Carolina and financed by the World Bank for simulation, design, and optimization of branched water distribution networks. The programs are free and are in the public domain. The program runs in MS DOS, but its user-friendly data entry editor, on-line help and a report generation routine provide a MS Windows like experience. The program is widely used across the world today by students, researchers, municipal engineers and professionals.

BRANCH 3.0 is used to design pressurized, branched (tree-type, non-looped) water distribution networks by choosing from among a set of candidate diameters for each pipeline so that the total cost of the network is minimized subject to meeting certain design constraints. Both construction costs and the design constraints can be expressed as linear, mathematical statements. The network is characterized by links (individual pipes) connected by nodes, which are points of flow input, outflow or pipe junctions. This version of the software can handle up to 125 pipes. BRANCH 3.0 formulates the linear programming model for the least cost design, solves the model and outputs the design as well as corresponding hydraulic information. Data required include description of network elements such as pipe lengths, friction coefficients, nodal demands and ground elevations, data describing the geometry of the network, the candidate diameters and their unit costs, and system constraints (minimum pressures, minimum and maximum gradients). Outputs include optimal lengths and diameters of pipes in each link, total network costs and hydraulic information.

LOOP 4.0 simulates the hydraulic characteristics of a pressurized, looped (closed circuit) water distribution network. The network is characterized by pipes and nodes (points of inputs/demand or pipe junctions). Data required are the description of the elements of the network such as pipe lengths, diameters, friction coefficients, nodal demands and ground elevation, and data describing the geometry of the network. The program outputs include flows and velocities in the links and pressures at the nodes. It does not accommodate inline booster pumps or pressure reducing valves. This version handles up to 1,000 pipes and can simulate up to 10 nodes with known hydraulic grade lines (e.g., storage reservoirs). It will accept any looped, partially looped / branched or completely branched network. LOOP's normal use is to simulate the hydraulic response of a network to a single or multiple input with at least one known hydraulic gradient line elevation. It also contains a sub-program for generating a cost summary once a final design is completed

GIS: Information not available.
CAD: Information not available.
Model Size: BRANCH: 125 pipes, 126 nodes, 30 diameters / LOOP: 1000 pipes, 750 nodes, 20 reservoirs, 20 booster pumps, 20 PRVs, 20 check valves, 30 diameters
OS: MS DOS
Head-loss Equations: Hazen-William, Darcy-Weisbach
SCADA Link: Information not available.
Presentations: Tabular, ASCII file, Printing, Graphic (LOOP). Its user-friendly data entry editor, on-line help and a report generation routine provide a MS Windows like experience.
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Security Specific: none
Calibration: Information not available.

Water Quality Analysis: none

Price: Free – Public Domain
Support: On-line help

CROSS (WaterPac®)

Rehm Software GmbH Großtobeler Strasse 41 8276 Berg / Ravensburg	Telephone: +49 751 560200 Fax: ++49 751 5602099 E-mail: info@rehm.de Internet: http://www.rehm.de/

General Description: CROSS is a hydraulic calculation for water supply pipes. The program package CROSS can be applied to carry out hydraulic calculations for both ring distribution systems and arterial distribution systems for the water-supply. Following elements can be considered in the program: hydrants, slide valves, reflux valves, spring feedings, transit shafts, pass elevated tanks, water towers and flow regulators. The water is fed in the pipes through centrifugal pumps, piston pumps and elevated tanks. Different pressure zones can be taken into account in the calculations through pressure regulators, pressure boostings as well as pressure reducing valves. In addition, the program can construct a site plan, if coordinates are available.

The results of the hydraulic calculation are provided to the following programs for further processing:
CROSSDESIGN: Graphical planning system for water supply pipes
CROSSPLOT: Drawing longitudinal sections of the pipe lines
CROSSPLAN: Drawing pipe-line plans for the water supply
WERTWASER: Property assessment for water supply pipe-lines

GIS: Information not available.
CAD: AutoCAD from R2000 or AutoCAD Map from R4 is required to use CROSSDESIGN
Model Size: Maximum 3 operating states can be considered with maximal: 10,000 pipes or nodes, 60 supply areas, and 13 different pipe elements (each 30). Up to 5 pipes may be connected to a node. If more inflows should be available, the other inflows can be included by inserting fictitious nodes behind the current node.
OS: Microsoft® Windows™ (Me, XP, 2000, NT4.0)
Head-loss Equations: The hydraulic calculations are performed according to the formula of Prandtl-Colebrook and the resistance formula of Darcy.
SCADA Link: Information not available.

Presentations: Following can be printed on screen, printer, or in an ASCII-file for three operating states: node list, pipe list, elevated tank list, pump list, pressure change list, statistic list, and site plan.
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.

Security Specific: Information not available.
Calibration: Information not available.

Water Quality Analysis: Information not available.

Price: Information not available.
Support: On-line help, FAQ, demo CD

EPANET (Version 2.0)

U.S. Environmental Protection Agency
Ariel Rios Building
1200 Pennsylvania Avenue, N.W.
Washington, DC 20460

Telephone: (202) 272-0167
Internet: www.epa.gov

General Description: Program developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. Specifically developed to help utilities maintain and improve the quality of water delivered to consumers through their distribution systems. Program contains a Windows user interface that provides a visual network editor that simplifies the process of building and editing the network. EPANET was specifically developed to help water utilities maintain and improve the quality of water delivered to consumers through their distribution systems. It can be used to design sampling programs, study disinfectant loss and by-product formation, and conduct consumer exposure assessments. It can assist in evaluating alternative strategies for improving water quality such as altering source utilization within multi-source systems, modifying pumping and tank filling/emptying schedules to reduce water age, utilizing booster disinfection stations at key locations to maintain target residuals, and planning a cost-effective program of targeted pipe cleaning and replacement.

GIS: EPANET does not have any direct linkages to external GIS.
CAD: EPANET does not have any direct linkages to external CAD.
Model Size: No limitations on size. Handles systems of any size
OS: Microsoft® Windows™ (95/98/NT)
Head-loss Equations: Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas
SCADA Link: Information not available.
Presentations: Various data reporting and visualization tools are used to assist in interpreting the results of a network analysis. These include graphical views (time series plots, profile plots, contour plots, etc.), tabular views, and special reports (energy usage, reaction, and calibration reports).
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Security Specific: Information not available.
Calibration: Includes calibration report, which shows how well the simulated results match the measurements taken from the modeled system. This includes three separate reports—statistics page, correlation plot page, and mean comparisons page. The statistics page lists various errors between those simulated and observed values at each location. The correlation plot is a scatter plot of the observed and simulated values, with each location having a different color. The plot should have a 45-degree angle line. The mean comparisons page is a bar chart that compares the mean observed and mean simulated values for the calibration parameters at each location they were taken.
Programmer's Toolkit: Computational engine can be changed through the dynamic link library (DLL). This allows program to be modified to meet specific needs of modeler. The functions can be incorporated into 32-bit Windows applications written in C/C++, Delphi Pascal, Visual Basic, or any other language that can call functions within a Windows DLL. The toolkit has over 50 functions that can be used to open a network description file, read and modify various network design and operating parameters, run multiple extended period simulations accessing results as they are generated or saving them to file, and write selected results to file in a user-specified format. Can be useful for developing specialized applications (optimization or automated calibration models) that require running many network analyses as selected input parameters are iteratively modified. Windows Help File that explains how to uses these.
Reports: Numerous data reporting and visualization tools included. Can view results in different formats: color-coded network maps, data tables, time series graphs, and contour plots. Includes graphical views (time series plots, profile plots, contour plots, etc.), tabular views, and special reports (energy usage, reaction, and calibration reports). Animation is also available when a node or link viewing parameter is a computed value.

Water Quality Analysis: EPANET's water quality analyzer can model the movement of a non-reactive tracer material through the network over time; model the movement and fate of a reactive material as it grows (e.g., a disinfection by-product) or decays (e.g., chlorine residual) with time; model the age of water throughout a network; track the percent of flow from a given node reaching all other nodes over time;

model reactions both in the bulk flow and at the pipe wall; allow growth or decay reactions to proceed up to a limiting concentration; employ global reaction rate coefficients that can be modified on a pipe-by-pipe basis; allow for time-varying concentration or mass inputs at any location in the network, and model storage tanks as being either complete mix, plug flow, or two-compartment reactors.
Price: Free -- public domain. **Support:** None. The University of Guelph has established an EPANET Users Listserve, which allows subscribers to ask questions and exchange information.

H_2OMAP/H_2ONET

MWH Soft 300 North Lake Avenue, Suite 1200 Pasadena, CA 91101	Sales: 626-568-6868 Support: 626-568-6869 Fax: 626-568-6870 Internet: http://www.mwhsoft.com/

General Description: H_2OMAP can analyze entire system through either steady-state or extended period simulations. It includes minor head losses. It has a unique open-architecture framework that makes it easy to manage and distribute geospatial data and exchange modeling information with other applications.

H_2ONET Analyzer a powerful and complete water distribution modeling, analysis, and design software. It performs fast, reliable, and comprehensive hydraulic and dynamic water quality modeling, energy management, real-time simulation and control, fire flow analysis, unidirectional flushing, and with automated on-line SCADA interface. The program can also be effectively used to analyze pressurized sewer collection systems. H_2ONET Analyzer can build and maintain "custom" modeling database; perform comprehensive dynamic water quality simulations, and analyze the entire system or any selected portions

GIS: Provides powerful and practical stand-alone GIS-based program.
CAD: Integrate with AutoCAD 2002 (Version 3.5 or 4.x) or with AutoCAD 2004/2005 (Version 5.x). Based on AutoCAD graphics, H_2OMAP optimizes on-line data integration and bi-directional information exchange for complete network model creation and maintenance, eliminating time-consuming translations and ensuring data integrity and reliability.
Model Size: No limit in unlimited version (largest client has 40,000 pipes).
OS: Microsoft® Windows™ (95, 98, NT, 2000, Me)
Head-loss Equations: Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas
SCADA Link: SCADA interface included. Monitor water tank levels, pump status and speed, valve status and settings, and demands. Alarms can also be incorporated. It can compare pressures and flows from all modeled items.
Presentations: Array of tools, to include color-coded maps, graphs, profiles, tabular reports that can be customized, and animation.
ArcSDE/Geodatabase Compatibility: Fully supports ArcSDE 8.1, ArcSDE versioning and ArcSDE Direct Connect Support. These allow management of geographic information in one of four databases: IBM DB2, Informix, Microsoft SQL Server, and Oracle.
Scenarios: H_2OMAP has a tree-type scenario manager—each change cascades through all the projects. This allows an array of alternatives to be modeled for one single model. This allows different models to be compared instantly. Data can be inherited through the different scenarios. The inheritance can be from parent to child or vice versa.
Security Specific: H_2OMAP also has various advanced water security tools which include event/consequence management, vulnerability assessment, tracking contaminants to the originating sources, computation of purge volumes, event isolation, and customer report notification generation.
Calibration: Calibration is available also through the use of genetic algorithm. This can include multiple scenarios calibration and complete EPS calibration

Water Quality Analysis: The program can conduct water age, trace, and constituent analysis. It tracks the movement and fate of water quality constituents as it grows or decays up to a limiting concentration. The constituent can be conservative or reactive. It analyzes kinetic reactions both in the bulk flow and at the pipe wall. Incorporates n-th order kinetics to model reactions in bulk flow. Uses zero order or first order kinetics to model reactions at pipe wall. Accounts for mass transfer limitations when modeling pipe wall reactions. The global reaction rate coefficient can be modified on a pipe-by-pipe basis. Wall reaction rate coefficients can be correlated to pipe roughness. Models storage tanks as complete mix, plug flow, or 2-compartment reactors.

Price: See charts below for pricing.
Support: 1st year free then \$800/yr (\$1,000/yr for platinum plan); toll free phone support; On-line help; Free upgrades, software and engineering support. Continuing education workshops offered.

Number of Links	100	250	500	1000	2000	3000	4000	5000	6000	10000	No limit
H_2OMAP Water 4.5	$1,000	$1,500	$2,000	$4,000	$5,000	$6,000	$7,000	$8,000	$9,000	$13,000	$14,000
Gold MSP	$800	$800	$800	$800	$800	$800	$800	$1000	$1000	$1000	$1000
H_2OMAP Water Suite 4.5	n/a	n/a	N/a	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000	$14,000	$15,000
Extensions:											
Platinum MSP	n/a	n/a	N/a	$1,000	$1,000	$1,000	$1,000	$2,000	$2,000	$2,000	$2,000

Extensions: Schedules, Calibrator®, Advisor®, Tracer®, Skeletonizer, Designer, WQ Calibrator.
All prices shown are in US dollars and apply to both local and network installations. For certain international countries, local taxes may apply. Free Software Maintenance applies for the first subscription period. Receive a 10% discount for the 2nd subscription period with purchase of two (2) consecutive years of Annual Subscription Program (MSP) - Call for details. Receive a 15% discount for the 2nd and 3rd subscription periods with purchase of three (3) consecutive years of Annual Subscription Program (MSP) - call for details.

Number of Links	100	250	500	1000	2000	3000	4000	5000	6000	10000	No limit
H_2ONET Analyzer 5.1/4.7	$1,000	$1,500	$2,000	$4,000	$5,000	$6,000	$7,000	$8,000	$9,000	$13,000	$14,000
Gold MSP	$800	$800	$800	$800	$800	$800	$800	$1000	$1000	$1000	$1000
H_2ONET Suite 5.1/4.7	n/a	n/a	N/a	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000	$14,000	$15,000
Extensions:											
Platinum MSP	n/a	n/a	N/a	$1,000	$1,000	$1,000	$1,000	$2,000	$2,000	$2,000	$2,000

Extensions: Schedules, Calibrator®, Advisor®, Tracer®, Skeletonizer, Designer, WQ Calibrator
All prices shown are in US dollars and apply to both local and network installations. For certain international countries, local taxes may apply. Free Software Maintenance applies for the first subscription period. Receive a 10% discount for the 2nd subscription period with purchase of two (2) consecutive years of Annual Subscription Program (MSP) - Call for details. Receive a 15% discount for the 2nd and 3rd subscription periods with purchase of three (3) consecutive years of Annual Subscription Program (MSP) - call for details.

Helix delta-Q (Version 2.28)	
Helix Technologies Pty Ltd PO Box 610 Morley, WA 6943 Australia	Telephone: +61 8 9275 0635 Fax: +61 8 9275 0615 Sales and Support: helix@vianet.net.au Internet: http://www.helixtech.com.au/

General Description: **delta-Q** is a powerful tool for engineers and equipment suppliers to quickly and easily design and optimize pipe networks for compressible and incompressible fluids. It can calculate friction losses and pressure drop in pipes and fittings for Liquids, Slurries and Gasses. Model complex process flow pipe networks and solve for unknown flow rates and node pressures at the press of a button.

The program considers pumps, tanks, junctions, nozzles (sprinklers) and any fittings such as bends, valves, tee's, etc. It can calculate friction losses and pressure drop in pipes and fittings for liquids, slurries and gasses. It models complex process flow pipe networks and solves for unknown flow rates and node pressures at the press of a button. delta-Q has database files for liquids, slurries, gasses, pipes, pipe fittings and pumps. Data from the database files can be pasted by clicking on an element in the network diagram.

The program was developed in 1991. A powerful new network analysis engine was added in 1998 that utilized linear theory and Newton Raphson methods. A CAD DXF file generator was added in 1999 for creating large drawings of complex networks. Some features of the actual version are: wuick and easy to use and very powerful network analysis engine; drag and drop network components onto the screen for quick and easy network creation; add individual fittings to pipes using the fitting database or enter an estimate of the total K value; calculate fitting losses using the standard K value method or the Kf method, which compensates for fluid viscosity and turbulence; display the network calculation results such as pipe flows, velocity, head loss, node pressure and many others on the network diagram; network reports' display and print the network pipe and node data as well as calculation results; click on a pipe to view the system curve with the network duty point shown.

GIS: Information not available.
CAD: Information not available.
Model Size: Unlimited number of pumps, tanks, junctions, sprinklers, pipes and fittings and valves, etc.
OS: Microsoft® Windows™ (NT, Win 95 or 98)
Head-loss Equations: Colebrook, White, Hazen-William, Darcy, Linear Theory and Newton Raphson Network Analysis engine. Orifice plate calculator included and also Settling Slurry, Bingham Plastics and Compressible Fluid (Isothermal and Modified Darcy method)
SCADA Link: Information not available.
Presentations: The network diagram and system head curves can be printed and Design Reports are produced
simply in a compact table format which can be printed or pasted into MS Excel™, Lotus 1-2-3™ or any other Windows compatible spreadsheet or word processor. The network solution can be viewed in graph form.
This allows user to check for minimum or maximum values at a glance. Export data to Excel and create a CAD DXF file drawing of the network at the click of a button. This documents the complete design, on an easy to read format drawing up to A0 in size.
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Security Specific: Model 'what-if' scenarios - closes off certain pipes and views the effects on the network.
Calibration: Information not available.

Water Quality Analysis: Information not available.

Price: See chart below for pricing.
Support: The program is supplied with a fully integrated context sensitive help system. Formulae and calculation methods are detailed in the manual and help file. Help-online, annual support contract offered, web page downloads, after sales service provided via the internet and e-mail.

Description	Version	Price Au$ Excl GST	Price Au$ Incl. GST
Helix **delta-Q Pipe Networks** Program for Liquids, Slurries & Gases	2.0	$1,850	$2,035
Helix **delta-Q PumpManager** Program	1.0	$950	$1045
Annual Software Support Contract	15% of Price		
Shipping to within Australia	-	$20	$22
Shipping to outside Australia	-	$68	$68

All Prices exclude GST. From 1 July 2000 Australian customers must allow an additional 10% for GST. Shipments to outside Australia are exempt from GST.
All prices are listed in Australian Dollars and are subject to change at any time. *One Australian dollar is approximately equal to 73 US cents.* The actual rate of exchange ruling at time of order should be checked by the purchaser. Please enclose payment for the total amount. Payments must be in Australian Dollars, with cheques drawn on an Australian Bank, or send international postal money orders in Australian Dollars. VISA, Amex and MasterCard Credit Card payments will be accepted provided all details are submitted correctly. Company Purchase orders are accepted subject to conditions.

InfoWater™ Protector	
MWH Soft 300 North Lake Avenue, Suite 1200 Pasadena, CA 91101	Sales: 626-568-6868 Support: 626-568-6869 Fax: 626-568-6870 Internet: http://www.mwhsoft.com/

General Description: InfoWater™ is a fully GIS-integrated water distribution modeling and management software application. Built atop ArcGIS™ using the latest Microsoft .NET and ESRI ArcObjects component technologies, InfoWater™ seamlessly integrates advanced water network modeling and optimization functionality with the latest generation of ArcGIS™. InfoWater™ capitalizes on the intelligence and versatility of the geodatabase architecture to deliver unparalleled levels of geospatial analysis, infrastructure management and business planning. Its unique interoperable geospatial framework enables world-record performance, scalability, reliability, functionality and flexibility - all within the powerful ArcGIS™ environment.

InfoWater Protector represents the state-of-the-art in water security planning, force protection, and vulnerability assessment. Includes expanded power and flexibility in estimating the consequences of a terrorist attack or a crisis event on the drinking water supply infrastructure as well as formulating and evaluating sound emergency response, recovery, remediation and operations plans, and security upgrades.

GIS: Fully automate GIS data exchange with ESRI data sources -- pick any GIS attributes automatically without mapping any fields. InfoWater™ extends the core features of ArcGIS™, providing a comprehensive geospatial environment for complete network model construction, graphical editing, network simulation, results presentation, map generation, and enterprise-wide data sharing and exchange. It also adds rich discipline-specific functionality to ArcGIS™ designed to streamline and facilitate all aspects of the water distribution modeling workflow.

CAD: The Network Review/Fix Tool is a comprehensive network drawing examination and correction application for use in constructing reliable, credible working models ready for analysis. It offers users complete functionality to quickly identify and automatically correct any network topology problems (e.g., disconnected nodes) and data flaws (e.g., duplicated pipes or nodes) that may arise from digitizing a model or building it using pre-existing GIS and CAD datasets.

Model Size: No limit on the size (unlimited link version).

OS: Microsoft® Windows™ (95, 98, NT, 2000, Me)

Head-loss Equations: Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas

SCADA Link: Provides on-line SCADA interface with alarms.

Presentations: InfoWater™ easily makes colorful, fully dimensional visualizations. Generates beautiful, accurate, and smooth contours for any variable, including elevation, pressure, hydraulic grade line, demand, water age, chlorine concentration, and more, directly on the map, overlay contours on single drawing.

ArcSDE/Geodatabase Compatibility: Information not available.

Scenarios: Includes comprehensive tree-type scenario manager. Every change made cascades through the entire set of projects in an easy-to-use, tree-like structure, allowing the modeler to switch between scenarios, compare input data, merge models, and compare results instantly. Reverse (child to parent) inheritance is also fully supported.

Security Specific: InfoWater Protector allows the user to model the propagation and concentration of naturally disseminated, accidentally released, or intentionally introduced contaminants and chemical constituents throughout water distribution systems; assess the effects of water treatment on the contaminant; and evaluate the potential impact of unforeseen facility breakdown (e.g., significant structural damage and/or operational disruption). Enables the user to locate areas within the system affected by contamination; calculate population at risk and report customer notification information; and identify the appropriate valves to close to isolate a contamination event. Helps track contaminants to originating source(s); compute required purging water volume; develop efficient flushing strategies; determine the resulting impact on fire-fighting capabilities; and prepare data for eventual prosecution.

Calibration: Performs online calibration.

Water Quality Analysis: Same as for H_2OMAP/H_2ONET

Price: See chart below for pricing.

Support: Information not available.

InfoWater														
No. of Licenses														
No. of Links	100	250	500	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	Unlimited
Price	$1,000	$1,500	$2,000	$4,000	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000	$11,000	$12,000	$13,000	$14,000
InfoWater Suite														
No. of Licenses	n/a	n/a	n/a											
No. of Links	100	250	500	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	Unlimited
Price	n/a	n/a	n/a	$5,000	$6,000	$7,000	$8,000	$9,000	$10,000	$11,000	$12,000	$13,000	$14,000	$15,000
For additional information or to place order call (626) 568-6868 or 568-6869														

MIKE NET 2002

BOSS International Corporate Headquarters 6300 University Avenue Madison, WI 53562-3486	Sales: 800-488-4775 Tech Support: 608-258-9910 or support@bossintl.com Fax: 608-258-9943 Internet: http://www.bossintl.com/

General Description: MIKE NET can analyze an entire water distribution system, or selected portions, under steady state or extended period simulations, with water quality analysis if needed. Network models can be quickly developed, using a variety of different means. Network components can be read-in directly from an ArcInfo®, ArcFM®, ArcView®, or MapInfo® GIS, or can be interactively created using a mouse by simply pointing and clicking. Graphical symbols are used to represent network elements such as pipes, junction nodes, pumps, control valves, tanks, and reservoirs. MIKE NET allows the user, at any time, to interactively add, insert, delete, or move any network component, automatically updating the modeling database. Selecting and moving a node automatically moves all connected pipes, valves, and pumps. In addition, data can be shared with any standard Windows spreadsheet (e.g., Microsoft Excel) or relational database (e.g., Oracle®, Microsoft SQL Server, Informix®, Sybase®) either directly or using ODBC links, or by simply cutting to and pasting from the Microsoft Windows clipboard.

GIS: MIKE NET can share water distribution data with any ArcInfo, ArcFM (Facilities Manager), ArcView, or MapInfo GIS database. It can intelligently build a link to any GIS database structure, using attribute mapping and geocoding.

CAD: Input data and output results can be transferred to AutoCAD® and MicroStation® by a DXF file, allowing the network plan and analysis results to be exported.

Model Size: Can analyze the entire system or selected portions. Can handle large models and complex networks.

OS: Microsoft® Windows™ (95, 98, NT), network capability

Head-loss Equations: Pipe frictional loss computations can be performed using Hazen Williams, Darcy Weisbach, or Manning equations.

SCADA Link: MIKE NET-SCADA can be linked to any existing SCADA monitoring system. Consists of two modules: MIKE NET-SCADA On-Line and MIKE NET-SCADA Off-Line. MIKE NET-SCADA On-Line links directly to the SCADA system and will automatically perform continuous simulation runs based upon a predefined schedule—such as every 15 minutes. During each cycle, all measured SCADA data is imported into the network model and the model parameters updated. Then, a hydraulic and water quality model is performed. After the analysis, output data from the model is stored in the SCADA historical database, as well as displayed on the screen. Animations of computed values, such as water quality, can be performed. MIKE NET-SCADA Off-Line enables the user, at any time, to load a previously stored network model—which has been prepared and analyzed by MIKE NET-SCADA On-Line— and inspect the model results in greater detail.

Presentations: Comprehensive input data and output analysis reports can be automatically generated using the provided report templates. MIKE NET allows full customization of input and output reporting using Crystal Reports® report generator. Crystal Reports is a powerful database reporting and query tool, integrated directly into MIKE NET, providing a streamlined approach to creating reports. This allows the user unlimited flexibility and functionality in developing specialized user-defined reports. These reports can be fully customized to meet any combination of modeling criteria for any network variable and for any time period, or for simply adding a corporate logo, etc. Furthermore, due to MIKE NET's open-architecture Microsoft Access database engine, nearly any other reporting tool can be used to generate reports from MIKE NET.

ArcSDE/Geodatabase Compatibility: Information not available

Scenarios: MIKE NET provides an easy-to-use inheritance-tree type scenario manager, allowing different scenarios to be applied to the base water distribution model. This helps the user maintain a single model of the water distribution system and then quickly construct, apply, and evaluate different scenarios as they relate to the model. Scenarios can be cut, copied, and pasted between different branches in the inheritance-tree window, allowing the user to quickly combine different scenarios for a particular modeling concern. Scenarios are cumulative—as additional scenarios are applied on a branch in the inheritance-tree window, the changes to the base model are included. In addition, a batch analysis feature is provided, allowing the

user to select which scenario(s) to analyze, and then having the software automatically run the different scenarios. MIKE NET' scenario manager also allows modeler to add and delete network elements, such as pipes, pump stations, valves, as well as add and delete network submodels for each scenario. This enables to modeler to analyze master plans with future growth and land use changes in mind. **Security Specific:** The analysis engine allows modeling of "what if" scenarios, allowing the engineer to specify multiple modeling alternatives on the same pipe network. These alternatives can include user-selected changes in network configurations, demand loading conditions, and changes in physical system characteristics. MIKE NET' analysis engine can be run interactively, or in batch mode—automatically running several different scenarios on the same network. Either method allows rapid and efficient analysis of multiple modeling alternatives. **Calibration:** An automated network model calibration and optimization module is included with MIKE NET, based upon a genetic algorithm and optimal control computational scheme. This module allows the modeler to quickly calibrate the model to match field observations, thereby validating the credibility of the network model for reliable and cost-effective engineering and planning decisions with regard to network design, rehabilitation, expansion, and replacement. The user can define what pipes in the model can have their roughness adjusted to meet observed values, as well as define the allowable range of values that can be used. In addition to calibrating the model, this module can also be used to quickly troubleshoot the model. It can automatically locate where potentially closed, degraded, or leaking pipes are located within the actual network system—allowing the modeler to assist in maintenance and rehabilitation of the system.
Water Quality Analysis: MIKE NET will track the movement and fate of water quality constituents (such as chlorine, chloramine, trihalomethane, total dissolved solids, nitrates, hardness, fluoride, etc.) throughout the entire network during a dynamic simulation. MIKE NET accurately models phenomena such as first-order reactions within the bulk flow, pipe wall, and storage tanks. A global kinetic rate coefficient can be assigned for the entire network or user-specified values can be assigned to selected components. Water age, travel time, and constituent source tracking can also be performed.
Price: See charts below for pricing. **Support:** Company offers a wide range of consulting services. Technical support is unlimited. Claim that 96% of support calls returned within 1 hour (usually within 15 minutes). Offers training services.

MIKE NET without Water Quality	Price
MIKE NET with 250 Pipe Version	$ 995
MIKE NET with 500 Pipe Version	$1,995
MIKE NET with 1000 Pipe Version	$2,495
MIKE NET with 2,000 Pipe Version	$3,495
MIKE NET with 3,000 Pipe Version	$4,995
MIKE NET with 5,000 Pipe Version	$5,995
MIKE NET with 10,000 Pipe Version	$6,995
MIKE NET with Unlimited Pipe Version	$10,995

MIKE NET with Water Quality	Price
MIKE NET with 250 Pipe Version	$1495
MIKE NET with 500 Pipe Version	$2495
MIKE NET with 1000 Pipe Version	$3995
MIKE NET with 2,000 Pipe Version	$5995
MIKE NET with 3,000 Pipe Version	$7495
MIKE NET with 5,000 Pipe Version	$8495
MIKE NET with 10,000 Pipe Version	$9495
MIKE NET with Unlimited Pipe Version	$12495

optiDesigner (Version 1)

OptiWater	E-mail: info@optiwater.com Internet: http://www.optiwater.com

General Description: The OptiWater company specializes in optimization using Genetic Algorithms (GA). The products range from a general purpose GA to dedicated water network design and optimization software. They also can provide custom software for development services. Program currently has the following modules:

OptiGA 2.0.1: optiGA for VB is an ActiveX control (OCX) for the implementation of GA. No matter what is the nature of the optimization problem might be, optiGA is a generic control that will perform the genetic run for users.

optiDesigner 1.0: Windows software for optimal design of water distribution systems using GA. Program uses EPANET. Allows determination of most cost effective design, rehab, and system expansion. Program designs system pipes and finds minimal costs given constraints. Constraints can be minimum and maximum pressures at nodes; minimum and maximum velocities at network pipes, or maximum source flow

The system is drawn and the properties set using EPANET. The network is then exported to optiDesigner (as an INP file), which then runs the simulation once design options, pipes to be designed, junctions / sources constraints and optimization parameters have been set. Results can be listed or viewed using EPANET.

With optiDesigner it is easy find the most cost effective design, rehabilitation strategy and expansion strategy for a water distribution system. It can make a steady state design, do a design under a number of load patterns or run the design as an extended period simulation.

The development of optiDesigner version 2 is on its way. The next version will introduce new features like pumps design and scheduling, tank design and system.

GIS: Information not available.
CAD: Information not available.
Model Size: No limitation.
OS: Microsoft® Windows™ (95, 98, Me, NT, 2000, XP)
Head-loss Equations: Information not available.
SCADA Link: Information not available.
Presentations: List orientated, ASCII file (for text editor or spreadsheet), graphic through export of INP file to EPANET
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Services: They offer custom made software, including data manipulation, Data manipulation, hydraulic models, graphical user interface, EPANET Toolkit programming, optimization, and others.
Security Specific: OptiWater and Dr. Avi Ostfeld (Technion, Israel) have a new update that will include stochastic behavior of the system as well as a method to determine the source of contamination. No release date has been set, but some features will be showing at the WRPLM ASCE Conference in Salt Lake City this June.
Calibration: A network calibration module in development.

Water Quality Analysis: Information not available.

Price: Download the evaluation version of optiDesigner, this version is available for 30 days. To keep optiDesigner after the evaluation period, the user will be asked to register the commercial version of optiDesigner for only 350 US$. The installation package includes optiDesigner, samples, and optiDesigner's manual.
Support: User manual, e-mail support

PIPE2000/KYPIPE (Version 2)

Developed by Civil Engineering Software Centre 354 Civil Engineering Building University of Kentucky Lexington, KY 40506-0281	KYPIPE, LLC Software Center 3229 Brighton Place Lexington, KY 40509-2314 Telephone: (859) 263-2234 Fax: (859) 263-0401 E-mail: orders@kypipe.com Internet: http://www.kypipe.com/

General Description: PIPE2000 is a general-purpose pipe network hydraulic modeling program, which handles both steady state (KYPIPE2000) and transient (SURGE2000) analysis. KYPIPE2000 provides both hydraulic and water quality modeling. PIPE2000 is typically used for steady state and transient modeling municipal and rural water distribution systems. It is also widely used for hot, chilled, and process water systems. It is used for fire protection and irrigation sprinkler systems. It is also used for other liquids (oil, etc.).

Continuous research and development over the past 20 years has resulted in the most advanced hydraulic modeling capability available. KYPIPE 4 is the engine used for hydraulic calculations for the KYPIPE2000 modeling package. KYPIPE 4 is the fourth generation KYPIPE engine, which is the most widely used and trusted hydraulic analysis engine in the world. This engine has been an industry standard for 30 years and has been verified by numerous field tests and qualified for nuclear applications. It provides many capabilities not available with other hydraulic analysis engines. EPANET developed by the EPA (USA) is utilized by KYPIPE2000 for water quality modeling. SURGE2000 is a 6th generation transient flow modeling program, which carries out complex transient modeling.

Standard PIPE2000 node elements include junctions, tanks, reservoirs, pumps, sprinklers, rack sprinklers, regulating valves, loss elements, loss elements defined by manufacturer data from a library, variable pressure supplies, active valves, check valves, hydrants, valves, metered connections, surge control devices, inline meters, and user-defined devices, etc.

The strength of PIPE2000 is in its advanced modeling capabilities, which include the direct calculation of operational and design parameters, development of system curves, optimized calibration (GA), automatedatic ageing of pipes (roughness) and many other capabilities.

The PIPE2000 advanced graphical environment is extremely user-friendly, allowing graphical Model development and data entry. PIPE2000 has also been adapted to other calculation engines in addition to KYPIPE and SURGE. These include analysing gas (GAS2000), steam (STEAM2000), fire sprinkler systems (GOFLOW2000) and stormwater systems (STORM2000).

GIS: GIS compatible
CAD: AutoCAD compatible
Model Size: Up to 20,000 pipes. All type of nodes, reservoirs, pipes, pumps, valves, etc.
OS: Microsoft® Windows™ (95, 98, 2000, NT version 4.0 or higher)
Head-loss Equations: Hazen-William, Manning, Darcy-Weisbach
SCADA Link: Information not available.
Presentations: Graphic, ASCII file, AutoCAD, GIS, Excel
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Security Specific: Information not available.
Calibration: PIPE2000 uses an advanced optimization method based upon the genetic algorithm approach to optimally adjust pipe roughnesses, valve settings, tank levels, demand distribution, and other data to provide a calibrated model. The program minimizes the difference between observed field data (usually fire flow test data) and model predictions considering all test data simultaneously to provide the best calibration possible. The program directly utilizes the KYPIPE data file with a small amount of additional data (Calibration Data). PIPE2000 can save tremendous amount of time and produce better models through optimum calibration.

Because calibration is an essential step for good model development, Optimized Calibration module included at no additional cost in both the Standard and Professional versions of PIPE2000. This advanced capability is not available in most competing software packages. If available, it can cost up to $5000 to add this feature.

Water Quality Analysis: Automatedatic ageing of pipes (roughness) and many other capabilities.	
Price: See charts below for pricing. **Support:** FAQ, training courses, demo versions	

The 2000 Series Models	
Professional Features*	Add $500
Model	250-pipe Version
KYPIPE2000, Version 2 (Water Distribution)	$1,795
Upgrade from Version 1.x to 2.0	$495
Model	50-pipe Version**
KYPIPE2000 Version 2 (Water Distribution)	$350

* The professional version includes tools to interface to GIS and AutoCad files. These features work with all the analysis engines

**Additional Piping and Professional Features may NOT be added to this package. The $350 price may be credited toward an upgrade to a 250-pipe or higher version

Additional Pipe Pricing	
Upgrade from 250 to 1,000-pipe version	$500
Each additional 1,000 pipes, up to 20,000 pipes	$500

Network Version Pricing*	
Upgrade to Network Version (LAN server installation)**	$200
Additional concurrent users	See Multiple Copies Discount

* A network version may be accessed by any number of network users on 1 server. A network version will support concurrent users up to the number of purchased licenses.

**Network pricing is for single LAN server installation intended to serve a single site. If Network Version is to be used on a WAN, a license must be purchased for each location.

Discounts and Upgrade Credits

This is a comprehensive list of discounts and upgrades credits associated with the purchase of 2000 Series software packages and includes credits towards the purchase of other packages.

Multiple Model Discount	
For a single user, after the purchase of a 2000 Series model license (e.g., Gas2000), discount for each additional 2000 Series model (e.g., KYPIPE2000, Surge2000, etc.).	$500 off each

Multiple Copy Discounts	
License for one user for an organization	Full list price
License for one user at different site (same organization)	25% off list price
Additional users at licensed site	50% off list price

Upgrade Credits (credits are cumulative – see exceptions below)		
Credit For	**Upgrade To**	**Credit Towards List Price**
KY.TMP (Standard or Pro)	Pipe2000 (1,000 pipes or more)	$250
KYPIPE3, KYPIPE2, or KYPIPE	Pipe2000 (1,000 pipes or more)	$250
KY.TMP extra pipes: each 1,000 pipes over 1,000	Pipe2000 extra pipes: each 1,000 pipes over 1,000 – not exceeding number of KY.TMP pipes	$250

PipelineNet	
Technical Support Working Group, U.S. Environmental Protection Agency, Federal Emergency Management Agency, and others	Telephone: E-mail: TechTrans@tswg.gov Internet: http://www.tswg.gov/tswg/ip/PipelineNetTB.htm

General Description: In cooperation with the Federal Emergency Management Agency, the Technical Support Working Group (TSWG) has sponsored a project to develop software programs that would estimate the consequences of a terrorist attack on a city's drinking water infrastructure. The prototype system, PipelineNet, has been developed and is operational for Salt Lake City.

PipelineNet is a Geographic Information System (GIS)-based software tool with integrated database capability that can be used to model the flow and concentration of contaminants in a city's drinking water pipeline infrastructure. It contains a pipe network hydraulic model (EPANET), maps, and a US Census Population database. The PipelineNet model estimates the population at risk due to the introduction of contaminants in the public water supply and graphically maps this population.

The EPANET component of PipelineNet was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory.

GIS: The system uses Arc View GIS, which is integrated into the system.
CAD: Information not available.
Model Size: Information not available.
OS: The PipelineNet system is operational in the Microsoft® Windows™ 95/98/2000/NT environment on either laptop or desktop computers. The minimum requirements are 64Mb Ram, 500 Mb of free disk space. A CD-ROM drive is also required. The PipelineNet system also requires Arcview (version 3.2 or higher).
Head-loss Equations: Information not available.
SCADA Link: Information not available.
Presentations: Information not available.
ArcSDE/Geodatabase Compatibility: Information not available.
Scenarios: Information not available.
Security Specific: The PipelineNet model permits the user to model the flow and concentration of a biological or chemical agent within a city or municipal water system. This model assesses the effects of water treatment on the agent, models the flow and concentration of an agent through the water distribution system within a city or municipality, and calculates the population at risk. PipelineNet performs the following functions: simulates the flow and concentration of biological or chemical contaminants in a city or municipality's water distribution system; assesses the effects of water treatment on the contaminant; helps planners with present and future demand predictions; helps city managers with fire flow requirements; facilitates planning and design of distribution systems; aids in complying with drinking water regulations, and assesses risks to population.
Calibration: Information not available.

Water Quality Analysis: Uses EPANET for water quality analysis.

Price: Free – Public Domain
Support: Information not available.

Pipenet™	
Sunrise Systems Limited Flint Bridge Business Centre Ely Road Waterbeach, Cambridge CB5 9QZ	Telephone: 01223 441311 Fax: 01223 441297 Email: pipenet@sunrise-sys.com Internet: http://www.sunrise-sys.com/

General Description: PIPENET™ is used for fluid flow analysis on pipe and duct networks, including liquids, gases, and steam. The program can be used for design of systems or to or to troubleshoot existing systems.
Calculation Engine: The program uses proprietary calculation engine that ensures reliable results.
Library: The program includes data of fittings, pipe schedules, and properties of water, gases, and steam. The user can add to these. The fluid properties can either be constant or variable.
Program Modules: There are three program modules, each capable of standalone operation:
PIPENET Standard Module: Enables the flow analysis of networks for general use. Includes modelling of complex networks with all parameters, include pipes, ducts, fittings, pumps, filters, nozzles, orifices, etc.
PIPENET Spray/Sprinkler Module: Mainly for design of fire protection systems, including ring-mains, deluge systems, sprinkler systems, and foam solution systems.
PIPENET Transient Module: Provides method for modeling in-house transient analysis. Can be used for the following: pressure surges, calculating hydraulic transient forces, and modelling control systems in flow networks.

GIS: Information not available.
CAD: Information not available.
Model Size: Information not available.
OS: Microsoft® Windows™
Head-loss Equations: Information not available.
SCADA Link: Information not available.
Presentations: This can be created using Word, Write or PIPENET™ Output Browser. Meet mandatory requirements, as PIPENET™ results are acceptable to regulatory authorities.
Security Specific: Information not available.

Water Quality Analysis: The program has "what-if" scenarios, but is advertised for broken or blocked pipes.

Price: Information not available.
Support: All PIPENET™ modules are supplied with comprehensive documentation, which includes: tutorials, worked examples, user manuals, technical manuals, demo CD-ROMs. While PIPENET™ is easy to use even for those without prior experience; training courses are available to help users get the most out of the system. Hot line support in the use of PIPENET™ is available either direct from Sunrise Systems or from our authorized distributors.

STANET® (Version 7.3)	
Fischer-Uhrig Engineering Wuerttembergallee 27 D - 14052 Berlin Germany	Telephone: +49 30 300 993 90 Fax: +49 30 304 43 05 E-mail: info@stafu.de Internet: http://www.stafu.de
General Description: STANET is an integrated application for network analysis. Besides calculation, graphic input, output and a database browser is included. The browser may be displayed together with the graphics. STANET may be used as a network information system because it uses standard dBASE-III database files, which may be extended by the user. Because graphics and database are using the same files, data exchange with other applications is simple. The features of STANET are: flexible network constructions: calculated (i.e., unknown) and given values (pressure, inflow and load) may be set at different locations and in any number; calculation of additional values like temperature radiation into the ground and quality tracking; automated control of network topology with explicit messages for wrong or incomplete specifications; automated creation of subnetworks from closed valves and regulators; efficient functions for selective output of network parameters and results (filtering, sorting, grouping/classifying); output of background bitmap drawings (e.g., TIFF, BMP, etc.) and vector graphics (DXF AutoCad-12-Format); extensive configuration options; saving of commonly used settings (with names).	
GIS: Integration into GIS systems in batch mode (start calculation from another system). GIS/CAD interfaces for import of network data: AutoCAD; AutoGIS; GARONE/WARONE; Gradis 2000 (Straessle); IBM-GTIS: GPG; Magellan (Geoinform); Moskito; PARIS (Hemminger); Optiplan; Pegasus; ROKA; SICAD-SQD (Siemens); SINCAL **CAD:** Displaying background pictures in raster format (TIFF, BMP, etc.) or vector format (AutoCad DXF). **Model Size:** Only limited by the available memory. **Operating system:** Windows 9x/MW, NT 4.0, 2000, XP **Head-loss Equations:** Darcy-Weisbach, Prantl-Colebrook, Nikuradse **SCADA Link:** Information not available. **Presentations:** Information not available. **ArcSDE/Geodatabase Compatibility:** Information not available. **Scenarios:** Save the results of extended period simulation or single simulation results in a scenario. **Security Specific:** none **Calibration:** Information not available.	
Water Quality Analysis: Stationary mixing/tracking of contents (heating value, water quality, water age).	
Price: See chart below for pricing. Demo version with max. 15 nodes is free of charge. **Support:** On-line help, Q&A service, training, supplemental documentation, web page, free technical support via e-mail, telephone, fax, or remote control.	

STANET Price List (All prices in EURO and subject to change without notice. Taxes and duties are not included.)			
A.	**Standard Version:** STANET for Windows (32 Bit)		
	Basic modules with graphic functions (mouse/digitizer input, plotting/printing, import of ASCII files, attribute coloring, database functions, report generator, diameter calculation, graphical copy and paste), 32 bit version, manual in PDF format, 1 Medium		
	1. medium: gas, water, steam, district heating		
	1.000 nodes 2.100,00 2.000 nodes 3.100,00 5.000 nodes 6.200,00 10.000 nodes 7.700,00 20.000 nodes 10.300,00 >20.000 nodes 12.500,00		
B.	Additional medium: gas or water or district heating	60% of basic module	
C.	**Extensions:** (bp … basic price of A. or B.)		
C.1	Import of raster images (36 formats)	+20% from bp	Max. 800,00
C.2	Import of vector images DXF-R12	+20% from bp	Max. 800,00
C.3	Export of vector images DXF-R12	+20% from bp	Max. 800,00
C.4	Load forecast from statement of meter reading (VERBRA)	+20% from bp	Max. 1.600,00
C.5	Spatial profile diagram	+20% from bp	Max. 800,00
C.6	Automatic calculation of fire hydrant flows (water only)	+20% from bp	Max. 800,00
C.7	ArcView interface (SHAPE), Import and Export	+20% from bp	Max. 800,00
C.8	MapInfo interface (MID/MIF), Import and Export	+20% from bp	Max. 800,00
C.9	Stationary mixing/tracking of contents (heating value, water quality, water age) only g/w/dh		800,00
C.10	STANET-Viewer: only output on monitor and printer, no simulation, no input	20% from bp	
C.11	STANET-Edit-Print: only input and output, no simulation (e.g., workstation for digitizing)	40% from bp	
C.12	STANET-Calc-Viewer: only simulation and output (monitor and printer), no network input	40% from bp	
D.	**Options:**		
	Printed user manual (German, English)		30,00
	Dynamic simulation using GANESI, dynamic simulation using TASI for water		Call
	Import/Export from/to special systems (SICAD, Smallworld, GANESI, GEOGRAT, etc.)		
	Import from special systems (AutoGIS, Cubis-Polis, GRIPS, INGRADA, Magellan, PARIS, PolyGIS, etc.)		
	German, English or Polish version		
E.	**Discount for additional licenses:**		
	2 user:	50% of list price	
	3 to 5 users:	30% of list price, each license	
	Additional users:	Call	
F.	**Upgrades:**		
	Single upgrade to the latest version		Call
	Software maintenance		1,5% per month
	Upgrade from smaller to bigger standard version		Price difference
G.	**Installation and introduction:** one person each day (without costs for traveling or hotel)		800,00
H.	**Shipping**		15,00

WADISO SA (Version 4)	
Geustyn Loubser Streicher Inc. & GLS Engineering Software (Pty) Ltd. GLS Engineering Software PO Box 814 Stellenbosch 7599 South Africa	Telephone: +27 21 8800388 Fax: +27 21 8800389 E-mail: software@wadiso.com Internet: www.wadiso.com
General Description: WADISO SA is a comprehensive computer program for the analysis and optimal design of water distribution networks. It originated from the WADISO public domain model developed by Prof. Johannes Gessler of Colorado State University for the Army Corps of Engineers. The program performs steady state and time simulation analysis with the capability to optimize pipe, pump, and tank sizes for planning purposes, as well as water quality modeling. It is advertised as a local product with relevant international technology and as extremely user friendly, with menu driven structure and easy-to-use-and-understand interface between the graphical display/edit mode and the model database and results. It has a graphical display, with input and editing of any network element. It has seamless transition between modules. Non network data may also be displayed as background, e.g. parcel and street layouts.	
GIS: Can interface with GIS applications with the open input and output data structures (ASCII, Dbase IV, Paradox, Microsoft MDB) **CAD:** fully integrated high-speed, automatic conversion of CAD plan to hydraulic model, graphical editing and building of hydraulic model, thematic and SQL based query displays, support for large color background raster images, export of model to different CAD formats **Model Size:** Can handle over 10,000 nodes, depending on computer memory **OS:** Microsoft® Windows™ (95/98/Me/NT 4/2000/XP) Full 32-bit. **Head-loss Equations:** Hazen-Williams or Darcy-Weisbach **SCADA Link:** Can interface with SCADA on dynamic basis. In this, metered flows, pressures, tank levels, pump and valve status etc. are converted to relevant parameters and variables that are imported to update the data input files of simulations. **Presentations:** Provides flexible query system to map results and data. Output to large format color printers. Allows inclusion of age, material, pressures, pipes, or nodes. Graphical display of results, through color coding, arrows on pipes, different line thickness, different node sizes, etc., is available. Graphical display is always geographically correct, and not schematic. Bitmap images can also be imported as backdrop. **Calculation Technique:** Model uses a node method for calculation, which includes a non-linear loss equation for each junction being linearized and then substituted into the continuity equation at each node. A system of linear equations is thus made and solved through an iterative procedure. They stated that this has unique advantages because it allows excellent control over required and achieved accuracy. **Optimization Technique:** The program uses a straightforward algorithm employing "exhaustive enumeration." For this, the modeler specifies sizes for each pipe and then the model tests all possible combinations or pipe sizes, determining whether pressure constraints are met. **Security Specific:** Information not available.	
Water Quality Analysis: Program includes seamless interface to the public domain EPANet program for modeling of water quality aspects. In the EPS mode, using the EPANet program, the model can simulate more than a one-week period in one-hour time increments, and provides a comprehensive analysis of water quality aspects in a distribution system.	
Price: See chart below for pricing. **Support:** Annual maintenance (hotline during working hours and assistance with installation problems: 12.5%. On-line discussion forum called Wadiso SA.	

Wadiso SA 4.3 International Price List (for International Customers Outside of Southern Africa) Note that the website listed prices are current until 30 September 2002			
1.	**Wadiso SA 4 Basic Price for 1 Installation (1,000 Pipes, 1,000 Nodes)**		
	All Modules – Steady State Analysis, Timer Simulation, Water Quality Analysis and Optimization, inclusive of Reservoir Size Optimization and Windows Stand-alone Graphics Engine		$3,500
2.	**Increasing Program Capacity**		
2.1	Modules 1, 2, 3 & 4 – 2,000 pipes (add)		$500
2.2	Modules 1, 2, 3 & 4 – 5,000 pipes (add)		$1,000
2.3	Modules 1, 2, 3 & 4 – 10,000 pipes (add)		$1,500
2.4	Modules 1, 2, 3 & 4 – 15,000 pipes (add)		$2,000
3.	**Multiplier Factors for Increasing Number of Installations**		
	For multiple installations or a network installation purchased at the same time, the basic price (item 1 + item 2) should be multiplied by the following factors:		
		Factor with which basic price must be multiplied	
	Individual licenses:		
	1 License	1.0	
	2 Licenses	1.5	
	3 Licenses	2.0	
	5 Licenses	3.0	
	Network Licenses:		
	1 Roaming User	1.5	
	5 Concurrent Users	3.5	
	10 Concurrent Users	5.0	
4.	**Maintenance Contract**		
	Annual maintenance on the current full list price of Wadiso SA 4 software (items 1 + 2 above), consisting of:		12.5%
4.1	Hotline (telephone, fax, e-mail) available during working hours to provide:		
4.2	Assistance with installation problems		
4.3	Limited assistance with the performance of modeling and simulation		
4.4	Upgrades of the relevant version will be provided from time to time at no extra cost		
4.5	A 20% discount on the purchase price of additional installations of the program		
5.	**Notes**		
5.1	All prices are in US Dollars and include basic airmail shipping but not local duty taxes. As the US Dollars amount will be converted to South African Rand at the daily exchange rate, the final Dollar price might be slightly less than the quoted US Dollar price.		

WaterCAD

Haestad 37 Brookside Road Waterbury, CT 06708	Telephone: (800) 727-6555 General: info@haestad.com Support: support@haestad.com Internet: www.haestad.com

General Description: WaterCAD is a complete geographic information management system for water utilities in a cost-effective package. Allows analysis of water quality, determine fire flow requirements, calibrate large distribution networks, and more with WaterCAD's powerful hydraulic analysis tools.

WaterCAD is a sophisticated tool that enables engineers and decision makers to analyze and manage distribution networks with unprecedented accuracy and efficiency. The numerical computations of WaterCAD are based on the research by the U.S. Environmental Protection Agency (EPA) Drinking Water Research Division, Risk Reduction Engineering Laboratory, its employees, and consultants. Because of this, WaterCAD will generate consistent results as those obtained using EPANET.

Engineering Libraries: Comes with Haestad Methods' Engineering Libraries and Library Managers, which allows specification and modification objects, components, or common materials, which include materials, minor losses, and constituents
GIS: WaterGEMS links modeling with GIS.
CAD: Can be stand-alone or fully integrated. WaterCAD elements are fully accessible to all AutoCAD.
Model Size: Unlimited.
OS: Microsoft® Windows™ (98, ME, 2000, XP)
Head-loss Equations: Darcy-Weisbach, Chezy-Manning, Hazen-Williams
SCADA Link: Information not available.
Presentations: Create detailed reports for any element or group of elements and generate system-wide summaries and project inventories. Customize tables to present data in the order and format chosen and manipulate each table to suit system needs, making use of the built-in filtering, sorting, and editing tools. Visualize system bottlenecks quickly and create spectacular presentations with VCR-style controls for step-by-step visualization or dynamic animation. Watch color-coding, annotation, contouring, profiling, and tabular data update automatically. Generate fully customizable graphs of time-variable data such as tank levels, pump speeds, and pipe flowrates, and compare results from multiple scenarios on the same graph.
ArcVIEW: ArcView or ArcInfo integrated interface
Scenarios: Program provides scenario management, allowed analysis of unlimited "What If" calculations. The scenario contains all the data, options, results, and notes associated with a set of calculations. User can submit multiple scenarios for calculation, switch between, and then compare them. There are three basic types of scenarios: base, child, and manual fire flow. Base scenarios contain all the working data. Child scenarios inherit the data from base scenarios, and can reflect all or some of the data from the base scenario. Calculation options are not inherited between scenarios, but are duplicated when the scenario is first created. The alternatives and data records are inherited from the parent scenario so this is a permanent, dynamic link from a child back to its parent.
Security Specific: WaterCAD includes a scenario for selection of valves for contamination isolation and developing flushing strategies. It can also simulate the failure of critical water sources and identification of customers who will be impacted by the event. It allows quick responses by predicting the influence of these events and assessing the possible impacts of corrective actions. It also allows prioritization of physical security improvements according to component criticality and water system safety.
Calibration: Darwin Calibrator available for additional fee.

Water Quality Analysis: The program can conduct water age, trace, and constituent analysis. It tracks the movement and fate of water quality constituents as it grows or decays up to a limiting concentration. The constituent can be conservative or reactive. It analyzes kinetic reactions both in the bulk flow and at the pipe wall. Incorporates n-th order kinetics to model reactions in bulk flow. Uses zero order or first order kinetics to model reactions at pipe wall. Accounts for mass transfer limitations when modeling pipe wall reactions. The global reaction rate coefficient can be modified on a pipe-by-pipe basis. Wall reaction rate coefficients can be correlated to pipe roughness. Models storage tanks as complete mix, plug flow, or 2-compartment reactors.

Price: See charts below for pricing.
Support: ClientCare™ Program offered by Haestad includes the following: free upgrades, unlimited

professional support any time throughout the year, discounts on software, books, and training. The cost of the program is based on the level of support and is a percent of the software cost. The purpose of ClientCare is to keep the user up-to-date with the technological developments as well as access to technical and engineering support. If not subscribed, Haestad offers technical and engineering support on an emergency basis per incident.

The chart below shows the pricing of the WaterCAD, based on the model size:

# Pipes	**10**	**25**	**100**	**250**	**500**	**1000**	**2000**	**5000**	**10000**	**Unlim**
EZPay	$26	$58	$117	$224	$332	$547	$869	$1,084	$1,047	$1,622
Standard	$195	$495	$995	$1,995	$2,995	$4,995	$7,995	$9,995	$12,995	$14,995

EZPay allows purchase to be divided into monthly installments that are billed automatically. Each payment includes a processing fee.

The following are additional features that may be purchased.

Related Software Options	
Darwin Calibrator	$4,000
Darwin Designer	$4,000
Hammer	$4,995
Skelebrator	$4,000
WaterSAFE	$4,000

Support for the program is included below:

	One-Year Renewable Subscription	**Two-Year Subscription**
Gold Subscription Fee	35%	55%
Silver Subscription Fee	32%	52%
Bronze Subscription Fee	29%	48%

The percentages above are based on the software's current list price.

Appendix 2: Equipment Used

1720D Low Range Process Turbidimeter

The 1720D Low Range Process Turbidimeter is a continuous-reading nephelometric turbidimeter designed for low-range turbidity monitoring. Turbidity is measured by direction of a strong beam of light from the sensor head assembly down into the turbidimeter body. It takes readings at 90 degrees. Readings are detected by a submerged photocell. The amount of light read is proportional to the turbidity of the sample. If turbidity is low, little light will be scattered and detected. If the sample has high turbidity, it will cause a high level of light scattering and a high reading. A bubble trap stops the bubbles, which can interfere with the readings. Reading can be taken every 3 seconds (HACH, 1999).

Technical aspects are listed below:

- Range: 0 to 100 nephelometric turbidity units (NTU)
- Accuracy: ± 2% of reading or ± 0.02 NTU (whichever is greater) from 0-40 NTU; ± 5% of reading from 40 – 100 NTU
- Resolution: 0.001 NTU
- Repeatability: better than ± 1.0% or ± 0.002 NTU, whichever is greater
- Response time: for a full scale step change, initial response* in 1 min, 15 sec. Varies with flow. See chart on page 9.
- Sample Flow rate: 250-750 mL/minute (4.0 to 11.9 gal/hour)
- Operating Temp: 0 to 40 deg C

GLI Model C53 Conductivity Analyzer

Technical aspects are listed below:

- Operating Range: see manual because based on ranges selected, both in μS/cm and mS/cm
- Operation temp: -4.0 to 392 deg F or –20 to 200 deg C
- Accuracy: 0.1% of span
- Stability: 0.05% of span per 24 hours, non-cumulative
- Repeatability: 0.1% of span or better
- Temperature drift: zero and span: less than 0.03% of span/deg C (GLI International, Inc, No date a)

GLI Model P53 pH/ORP Analyzer

Technical aspects are listed below:

- Operating Range: -2.0 to 14.0 pH
  -2100 to 2100 mV
  -20 to 200 deg C
- Operation temp: -4 to 140 deg F (-20 to 60 deg C)
- Accuracy: 0.1% of span
- Stability: 0.05% of span per 24 hours, non-cumulative
- Repeatability: 0.1% of span or better
- Temperature drift: zero and span: less than 0.03% of span/deg C (GLI International, Inc., No date b).

CL17 Chlorine Analyzer

This analyzer is a microprocessor-controlled, process analyzer that is designed to monitor continuously a sample stream for chlorine content. It collects and analyzes samples every 2.5 minutes. The sample is collected in the colorimeter measuring cell where the blank absorbance is measured, which allows compensation for any turbidity or color in the sample and also provides a reference point. Reagents are then added to develop the magenta color, measured and compared to the reference. It uses a DPD Colorimetric Method which includes a N,N-Diethyl-p-phenylenediamine (DPD) indicator and a buffer, which are cause a red color to form with an intensity proportional to the chlorine concentration. The chlorine concentration is then measured photometrically (HACH, 2001).

The free available chlorine (hypochlorous acid and hypochlorite ions) in the sample oxidizes the DPD indicator reagent at a pH between 6.3 and 6.6, which forms a magenta-colored compound. The depth or intensity of the color is proportional to the chlorine concentration. The buffer used in the analysis maintains the proper pH. The total available chlorine (free available chlorine plus combined chloramines) can be determined through the addition of potassium iodide to the reaction. Chloramines in the sample oxidize iodide to iodine, which, along with any free available chlorine, oxidizes DPD indicator to form the magenta color at a pH of 5.1. A different buffer solution that contains potassium iodide maintains the pH at the proper level. After the chemical reaction is complete, the optical absorbance at 510 nm is compared to the absorbance that was measured through the sample before the reagents were added. The concentration of chlorine is calculated from the difference in absorbance (HACH, 2001).

Technical aspects are listed below:

- Operating Range: 0 to 5 mg/L free or residual chlorine
- Accuracy: ±5% or ± 0.035 ppm whichever is greater
- Precision: ±5% or ± 0.005 ppm whichever is greater
- Detection Limit: 0.035 ppm
- Cycle time: 2.5 minutes
- Sample Temp Range: 5 to 40 deg C (41 to 104 deg F)
- Inlet pressure to instrument: 1 to 5 psig; 1.5 psig is optimal

FilterTrak 660 ™ Laser Nephelometer

The laser nephelometer is optimized to measure turbidity in the critical range for filtered drinking water, which is in the range from 0 to 1000 mNTU. It is 150 times more powerful than a conventional turbidimeter and can detect particles smaller than 2.0 microns. Other drinking water instruments can detect particles smaller than 2.0 microns, but this instrument is not hindered by a theoretical lower limit to the particle size it can detect. The instrument can reliably detect at least as low a 5 mNTU. Based on the fact that it can detect sub-micron particles, it can provide much more accurate indication of filter ripening process as well as warnings for impending filter breakthrough. It can be calibrated and verified by using Hach's StablCal Stabilized Formazin, which is available at ultra-low range values from 100-800 milli-NTU (1 mNTU =0.001 NTU) (HACH, 2003).

The instrument works in the following manner:

1. A sample flows continuously into the device after a bubble trap that removes air.

2. A laser then projects bema through the water, which is a 660 nm, 35 mW solid-state laser diode. This light creates highly collimated, monochromatic beam, while stray light is virtually eliminated.
3. The light scattered is then collected at 90 degrees and carried through an optical fiber to a remote detection system. This amount of light is directly proportional to the sample turbidity. The turbidity is then calculated and reported as standard milli-Nephelometric Turbidity Units (mNTU).

Technical aspects are listed below:

- Range: 0.0 to 1000 milli Nephelometric Turbidity Units (mNTU) (0.0-1.0 NTU)
- Accuracy: ±5%of reading
- Resolution: 0.001 mNTU (0.000001 NTU)
- Repeatability: ±3.6% at 30 mNTU (0.03 NTU); ±1.7%at 800 mNTU (0.8 NTU)
- Flow Rate: 100-750 mL /min (1.6-11.9 gal/hour)
- Light Source: 660 nm Laser Diode; Class 1 Laser Product; Embedded 660 nm,Class 3B Laser Source
- Sample Temperature: 0 to 50 ° C

AstroTOC 1950 Plus

The 1950 Plus measures NPOC, or Non-Purgeable Organic Carbon, which is the non-volatile carbon left after the sample is purged (Parsons, 2002). Total inorganic carbon is the alkalinity in the sample, which is carbonates, bicarbonates, etc. This portion is removed from the sample through acidification and then escapes as a gas (Parsons, 2002). The remaining CO2 is proportional to the carbon concentration in the sample (HACH, 2002).

The analysis method used is UV persulfate oxidation with acid sparging for TIC removal followed by CO_2 NDIR detector measurement. This analysis is done in two-stages. First, the total inorganic carbon is removed through acidification, which leaves an inorganic-free sample.

The acidification takes place in the TIC sparger, which converts the inorganic carbon to CO2, which is then removed from the sample and vented (HACH, 2002). Phosphoric acid is delivered to the top of the sparger to complete this step (Parsons, 2002). The sample then contains only organic carbon, which is then pumped from the TIC sparger to the UV reactor for further analysis (HACH, 2002). Second, the analyzer converts the carbon in the sample to CO2 in a low temperature UV reactor, an oxidation process. For this, the sample is combined with the carrier gas and sodium persulfate, which promotes oxidation in the UV reactor. Here the carbon is converted to CO2, which is removed again from the sample at the gas liquid separator and routed to the IR detector. The IR detector then measures the CO2, which is proportional to the carbon concentration in the sample (HACH, 2002).

The instrument is factory calibrated for measurements of carbon dioxide from either 0 to 1000 ppm (0.1 %) or 0 to 10,000 ppm (1.0%). The response time is about 8 minutes, but the instrument is constantly taking samples (Parsons, 2002). The measurement range is from 0 – 5 up to 0 – 20,000 mg/L. The response is dependent on the range, but is usually less than or equal to 8 minutes. It is for indoor use, from 41-104 deg F use. Carrier gas should be clean, carbon dioxide free (HACH, 2002).

Appendix 3: *Cryptosporidium parvum* Data

Concentration: 50,000 oocysts/0.5 mL
Date: 13 November

	Tap water	Sample	Change
Chlorine	0.7	0.61	-0.09
Turbidity	0.401	0.145	-0.256
Conductivity	114	116	2
PH	7.96	7.88	-0.08
TOC	1.38	1.47	0.09

Concentration: 50,000 oocysts/0.5 mL
Date: 10 November

	Tap water	Sample	Change
Chlorine	0.58	0.44	-0.14
Turbidity	0.351	0.18	-0.171
Conductivity	123	122	-1
PH	7.76	7.76	0
TOC	1.24	1.3	0.06

Concentration: 5,000 oocysts/0.5 mL
Date: 13 November

	Tap water	Sample	Change
Chlorine	0.7	0.64	-0.06
Turbidity	0.401	0.128	-0.273
Conductivity	114	114	0
PH	7.96	7.88	-0.08
TOC	1.38	1.43	0.05

Concentration: 5000 oocysts/0.5 mL
Date: 6 November

	Tap water	Sample	Change
Chlorine	0.56	0.54	-0.02
Turbidity	0.784	0.182	-0.602
Conductivity	127	123	-4
PH	7.76	7.69	-0.07
TOC	1.42	1.43	0.01

Concentration: 1000 oocysts/0.5 mL
Date: 4 November

	Tap water	Sample	Change
Chlorine	0.58	0.51	-0.07
Turbidity	1.1	0.168	-0.932
Conductivity	129	123	-6
PH	7.74	7.68	-0.06
TOC	1.24	1.29	0.05

Concentration: 250 oocysts/0.5 mL
Date: 11 November

	Tap water	Sample	Change
Chlorine	0.56	0.53	-0.03
Turbidity	0.51	0.17	-0.34
Conductivity	124	117	-7
PH	7.75	7.74	-0.01
TOC	1.31	1.35	0.04

Concentration: 250 oocysts/0.5 mL
Date: 3 November

	Tap water	Sample	Change
Chlorine	0.64	0.65	0.01
Turbidity	0.742	0.363	-0.379
Conductivity	127	127	0
PH	7.96	7.76	-0.2
TOC	1.16	1.18	0.02

Concentration: 100 oocysts/0.5 mL
Date: 6 November

	Tap water	Sample	Change
Chlorine	0.52	0.48	0.04
Turbidity	0.767	0.149	-0.618
Conductivity	127	124	-3
PH	7.75	7.72	-0.03
TOC	1.42	1.45	0.03

Concentration: 16 oocysts/0.5 mL
Date: 11 November

	Tap water	Sample	Change
Chlorine	0.61	0.6	-0.01
Turbidity	0.427	0.551	0.124
Conductivity	121	121	0
PH	7.86	7.85	-0.01
TOC	1.31	1.31	0